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BEFORE THE BOARD OF PATENT APPEALS AND INTERFERENCES

Applicant:	David W. Farchmin
Serial No.:	10/675,608
Filed:	September 30, 2003
Title:	DISTRIBUTED WIRELESS POSITIONING ENGINE METHOD AND ASSEMBLY
Art Unit:	2688
Examiner:	Dai Phuong
Our Ref.:	110003.00057.03AB222

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APPEAL BRIEF OF APPELLANT

Dear Sir:

Applicant, David Farchmin, has filed a timely Notice of Appeal from the action of the Examiner finally rejecting claims 53-56, 58-70, 72-92, 96, 97 and 100-106 in this application.

i. Real Party in Interest

Rockwell Automation Technologies, Inc., owns all right, title and interest in this application.

ii. Related Appeals and Interferences

None

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iii. <u>Status of the Claims</u>

This application contains claims 53-92 and 96-107. Each of claims 53-56, 58-70, 72-81, 87-92, 100-104 and 106 has been finally rejected as being anticipated by US application publication No. 2003/0197643 (hereinafter "Fullerton"). In addition, each of claims 82-86, 96-96 and 105 has been finally rejected as being obvious over Fullerton in view of US patent No. 6,453,168 (hereinafter "McCrady"). The balance of the claims has been objected to as being dependent on rejected base claims. A copy of the claims on Appeal is enclosed in the Appendix (TAB A).

iv. <u>Status of Amendments</u>

A final rejection of claims 53-56, 58-70, 72-92, 96, 97 and 100-106 was rendered on July 28, 2006 that, among other things, rejected claims 53-56, 58-70, 72-92, 96, 97 and 100-106 as anticipated or obvious over various references. Applicant responded by filing an amendment after final on September 12, 2006. The Examiner responded via Advisory Action dated October 17, 2006 and maintained the final rejection. On September 22, 2006 Applicant filed the Notice of Appeal in this case.

No other amendments were filed after the filing of the Notice of Appeal.

v. <u>Summary of Claimed Subject Matter</u>

Independent claims 53, 82, 87, 96, 100 and 105 are appealed herein.

In general, the independent claims are drawn to methods for estimating the position of a wireless information device (WID) within a space where position information is wirelessly collected, a first subset of position information is used to identify a first position estimate, a second subset of position information is used to identify a second position estimate and then the two estimates are used

Referring to Fig. 6 and accompanying specification at paragraphs 63-65, claim 53 is drawn to a method for determining the location of a wireless information device 30 (see Fig. 1) within a space by (1) obtaining position information indicative of the distances of signal paths between the WID and specific locations (e.g., access points) within the space, (2) using a first sub-set of the position information to identify a first

estimate of WID location, (3) using a second sub-set of the position information to identify a second estimate of WID position and (4) using the first and second estimates to identifying a final estimate of the WID location.

Claim 82 is drawn to a method similar to the method of claim 53, albeit where there is a predefined preference for one estimate over another estimate such that if the one estimate is generated, that estimate is rendered accessible and only if the one estimate is not generated is the second estimate rendered accessible. To this end, referring to paragraph 19 of the specification as well as Fig. 6 and paragraphs 63-65, claim 82 is drawn to a method for determining the location of a wireless information device 30 (see Fig. 1) within a space by obtaining position information indicative of the distances of signal paths between the WID and specific locations within the space, (1) attempting to use a first sub-set of the position information to identify a first estimate of WID location, (2) attempting to use a second sub-set of the position information to identify a second estimate of the WID location, (3) when one of the first and second estimates is identified, rendering the one of the first and second estimates accessible by applications requiring WID location and (4) when the one of the first and second estimates is not identified and the other of the first and second estimates is identified, rendering the other of the first and second estimates accessible by applications requiring WID location.

Claim 87 is similar to claim 53 except that, instead of using first and second sets of position information to identify first and second position estimates, first and second position estimating systems (see 60 and 62 in Fig. 1) are used to generate the first and second position estimates. To this end, claim 87 includes the steps of tracking WID location with a first wireless position estimating system to generate a first position estimate, tracking WID location with a second wireless position estimating system to generate a second position estimate and then using the first and second estimates to identifying a final WID position estimate.

Claim 96 is drawn to a system wherein a position estimate is generated along with a confidence factor that indicates the likelihood that the estimate is accurate (see the third sentence of paragraph 13 of the specification), the confidence factor is

compared to a threshold requirement, when the confidence factor meets the requirement, the estimate is rendered accessible and when the confidence factor does not meet the threshold requirement, a different estimating process is performed. In this regard see Fig. 12 and paragraph 94 of the present specification.

Claim 100 is similar to claim 53 except that, instead of using first and second position information sets to identify first and second position estimates, first and second position estimating programs (see paragraph 84) are used to generate the first and second estimates. To this end see paragraphs 60-62 and Fig. 5 as well as paragraph 84 of the present specification that describe a method for estimating WID position by (1) generating a first WID position estimate via a first estimating program, (2) generating a second WID position estimate via a second estimating program and (3) using the first and second estimates to identify a final WID position estimate.

Claim 105 is drawn to a method wherein at least two position estimates are generated and a determination is made as to whether or not any of the estimates is sufficiently accurate and, where at least one of the estimates is sufficiently accurate, the most accurate of the estimates is rendered accessible and if none of the estimates is sufficiently accurate, another function is performed. This claim is supported in the specification at paragraphs 87 through 89 as well as by Fig. 13.

vi. <u>Grounds of Rejection to be Reviewed on Appeal</u>

1. Claims 53-56, 58-70, 72-81, 87-92, 100-104 and 106 have been held anticipated by Fullerton (Appendix TAB B).

2. Claims 82-86, 96-96 and 105 have been held obvious over Fullerton in view of McCrady (TAB C).

vii. <u>Argument</u>

A. Grouping of Claims

Claims 53, 59-66, 73-81, 82, 84-86, 100, 101, 105 and 106 are directed to the basic method of using position information to generate at least first and second position estimates and then using the first and second estimates to generate a final position

estimate and, in some cases, rendering the final estimate accessible, and therefore should be grouped together.

Claims 54-58, 67-72, 83, 87-92, 102-104 and 107 are directed to a method wherein confidence factors are generated for each position estimate and, in some cases, where the confidence factors are used to determine how to use the first and second estimates to generate the final estimate and therefore should be grouped together.

Claims 96-99 are directed to a method wherein a first position estimate and associated confidence factor are determined, when the confidence factor meets a threshold requirement the first estimate is rendered and when the confidence factor fails to meet the threshold, a second position estimate and associated confidence factor are determined and therefore should be grouped together.

B. The Present Invention

The present invention includes methods for accurately determining the position of a wireless information device (WID) (e.g., a palm type device, laptop, etc.) within an environment (e.g., a manufacturing facility). To this end, referring to Fig. 1 below, one way to determine the location of a WID 10 in an environment is to space apart several access points 12, 14, 16, etc., (e.g., wireless signal receivers) in the environment at known locations, cause the WID 10 to transmit signals to the access points 12, 14, 16 and then use the received signals to determine WID location using any of several well known triangulation processes. Thus, for instance, using a typical triangulation process, each received signal can be used to determine the distance (see D1, D2 and D3 in Fig. 1) between the receiving access point and the transmitting WID 10. Using the distances D1, D2 and D3 between WID 10 and three of the access points 12, 14 and 16, respectively, WID location can be determined. In a similar way access points may be used to transmit signals to the WID and the WID may be programmed to use the received signals to determine distances of the access points from the WID and then to generate a WID position estimate by triangulating using the distance estimates.

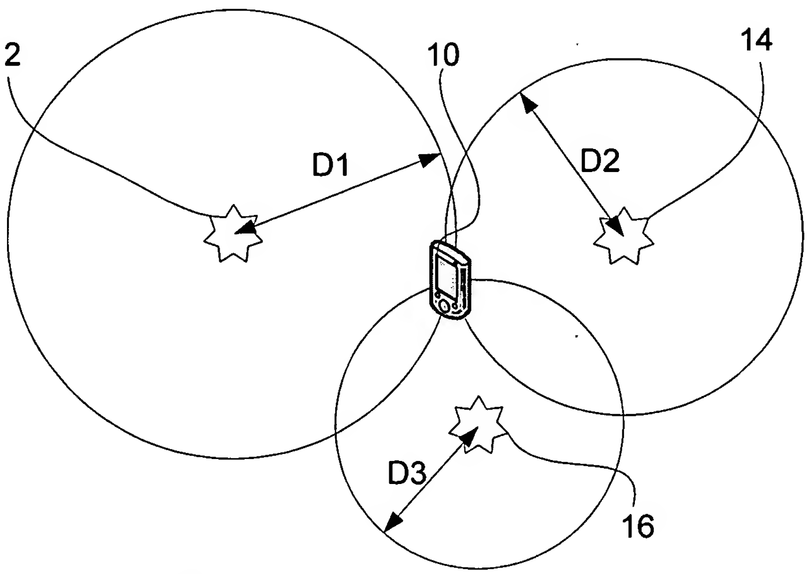

Fig. 1

Referring to Fig. 2, another way to estimate WID position is to use a system where a single stationary access point 20 includes a directional antenna 22 which, as the label implies, can be used to identify the direction from which a signal has been received. In this case, when a WID transmits a signal that is received by the access point, the signal can be used to determine the distance D4 between the WID and the access point. In addition, the directional antenna can be used to determine the direction from which the received signal was received. Using the distance and direction, the WID position can be determined.

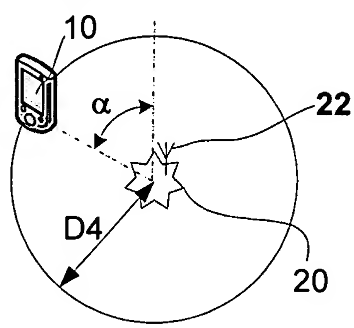

Fig. 2

Still other methods have been developed for estimating WID positions including statistical methods like the methods described in World patent application No. WO/02054813 which was cited in the background section of the present specification.

The present inventors have also recognized that, while there are several different wireless position estimating processes, which process will best estimate WID position may be dependent on characteristics of the space in which the WID operates. To this end, in open spaces that have few if any structures to obstruct wireless transmissions a typical triangulation procedure may optimally and most accurately estimate WID position. In a space that includes many obstructing structures, a statistical estimating process may be optimal. In some dynamic environments such as industrial facilities where large machines and work product are routinely moving, the optimal estimating process may be different at different locations within the industrial space and may in fact change for specific space locations as machines/work product is moves within the space.

In many applications extremely accurate position estimates are not required 100% of the time. For instance, in the case of wireless use of a laptop computer, if laptop position is off by a few yards for a short time, the system that includes the access points may simply select a less than optimal access point during the short time for communicating with the laptop.

In other applications, however, highly accurate position determinations are required essentially all the time. For instance, in an automated manufacturing plant where a WID is used to monitor and control proximate machines, if a position estimate is off by a few yards a WID user may be presented with information and control tools related to the wrong machine.

In order to increase the accuracy of WID position estimates, the present invention contemplates methods wherein two or more separate position estimating procedures are performed and where the results of the two separate position estimating procedures are used together to generate a final position estimate. Thus, for example, a first WID position estimate may be generated using a triangulation estimating method like the method described above with respect to Fig. 1 while a second WID position

estimate may be generated using a statistical analysis method. After the first and second estimates are generated, the first and second estimates are used together to generate the final estimate.

As another example, a first WID position estimate may be generated by triangulating using signals received from a first subset of three access points, a second position estimate may be generated by triangulating using signals received from a second subset of access points that is different than the first subset and then the two estimates may be used together to generate the final estimate.

As still one other example, signals received by three access points may be used to generate a first estimate, signals transmitted to the WID by a second set of three access points may be used by the WID to generate a second position estimate and then the first and second estimates may be used to identify the final position estimate.

In some circumstances it may be likely that one of two or more position estimates is more likely to be accurate than the other of the estimates. For instance, where signals received by first and second access point subsets are used to generate first and second estimates via triangulation, it may be that each of the first and second estimates clearly indicates that a WID is much closer to the first access point subset than to the second access point subset. In this case it will be likely that the first estimate is more accurate than the second estimate. In cases where one estimate is likely more accurate than other estimates, the estimates may be weighted and then combined to generate a final estimate. In the alternative, where one estimate is likely more accurate than other estimates, the likely more accurate estimate may be used as the final estimate and the other estimates may be discarded.

In order to compare different position estimates, in at least some cases the invention contemplates ascribing confidence factors to each estimate generated and then comparing the confidence factors in some fashion to determine how to use the different estimates to generate the final estimate.

In some embodiments position estimating procedures may be performed in sequence when confidence factors associated with existing estimates do not rise above a threshold level. For instance, according to at least some of the inventive methods,

when a first position estimating procedure generates a first position estimate and an associated confidence factor, the factor may be compared to a threshold value. When the factor is greater than the threshold value, the estimate may be published for use. However, when the factor is less than the threshold value, the system may be programmed to perform a second position estimating procedure thereby generating a second position estimate and associated confidence factor. This iterative process may continue until an estimate with a high confidence factor is generated and published.

C. Description of the Prior Art

Fullerton (US application publication No. 2003/0197643) teaches six different radio (i.e., WID) position estimating processes. The first and second processes are akin to the process described above with respect to Fig. 2 where a single access point that includes a directional antenna receives a signal from a mobile radio and the access point uses the received signal to estimate the distance between the access point and the radio and to estimate the angle or direction between the access point and the radio and then uses the distance and direction to determine the radio location. The third, fourth and sixth processes are similar to the triangulation process described above with respect to Fig. 1 where several stationary access points are used to generate distance estimates from a mobile radio to the access points and then the distances are combined to estimate radio position. The fifth embodiment is a hybrid embodiment where several stationary access points and at least one directional antenna are used to generate distance estimates and where the distance estimates and directional information are used to estimate radio position.

As an initial matter it should be noted that, while Fullerton teaches several different position estimating processes, Fullerton always teaches the processes as alternatives to each other and never once even remotely suggests a method where two or more of the separate processes should be performed to generate two estimates and then using the two estimates to identify a final estimate. In effect, Fullerton seems to assume that any one of the disclosed estimates will be sufficiently accurate for any

anticipated application and therefore there would be no reason to perform a second estimating process after a first process has been completed.

Referring now to Fullerton's paragraphs 105-112 and to Fig. 11, Fullerton's first position estimating method is described where, when the position of a first impulse radio 1104 is known, the position of a second impulse radio 1108 can be determined by having the first and second radios transmit sequential reference signals there between and using the signal propagation time to estimate the distance between the two radios (see first sentence in paragraph 111). After the radio to radio distance is determined, a directional antenna 1112 on the first radio determines a direction from the first to the second radio (see second sentence in paragraph 111) and then the direction and the distance are used to determine the position of the second radio (see paragraph 112). Thus, in this first method a distance is determined, a direction/angle is determined and then the distance and angle are used together to generate a <u>single position estimate</u>.

Referring to Fullerton's paragraphs 113 and 114, Fullerton's second estimating process includes a system wherein a universal clock is used to synchronize first and second radios, the time of flight of a signal from a first radio to a second radio is determined, the angle between the radios is determined using a directional antenna and then the angle and the distance values are used to determine the position of the second radio. Thus, in this second method, like the first method, a distance is determined, a direction/angle is determined and then the distance and angle are used together to generate a <u>single position estimate</u>.

Referring to Fullerton's paragraphs 115 through 116 and to Fig. 13, Fullerton's third estimating process includes stationary radios (i.e., access points) 1304 and 1308 and a mobile radio 1312 mounted to a movable object whose position is to be determined. Fullerton teaches that the <u>distances</u> d2 and d3 between radios 1304 and 1312 and radios 1308 and 1312, respectively, can be determined and used to identify the "<u>position</u>" (singular) (see paragraph 116, lines 11-14) of radio 1312 through use of a common triangulation method. Thus, while Fullerton's paragraphs 115 and 116 clearly

teach determination of two separate distances, the embodiment only identifies one position estimate by combining the two distances via a common triangulation method.

Referring to Fullerton's paragraph 117, according to the fourth estimating process, Fullerton teaches that a universal clock and distance estimates d1, d2 and d3 in Fig. 13 can be used to estimate position of a mobile radio.

Referring to Fullerton's fifth embodiment described in paragraph 118, a single position estimating process can be used to generate two position estimates and then directional antennas can be used to determine which of the two position estimates is the best estimate. To this end, referring also to Fig. 15, where locations of radios 1504 and 1508 are known (as is distance d1) and the system is attempting to determine the location of radio 1512, transmitted and received signals can be used to determine distances d2 and d3. Fullerton recognizes however that using only distances d1, d2 and d3 to determine the location of radio 1512 results in position ambiguity wherein position can only be narrowed to two locations (see (x3, y3) and (x3', y3') in Fig. 15). Thus, one position estimating process results in two position estimates. Here, Fullerton teaches that the ambiguity can be resolved by using directional information collected via directional antennas as opposed to using the two position estimates themselves.

Referring to paragraph 119 and Fig. 16, according to Fullerton's sixth process, a simple triangulation method can be used to resolve position ambiguity by providing three stationary radios for receiving signals from a mobile radio 1616 where each of the received signals is used to determine a distance between the receiving radio and the mobile radio. The distances between the radios are used to generate a single position estimate for radio 1616.

The balance of the Fullerton specification simply discusses various versions of the embodiments described above.

Referring to McCrady's Fig. 1, McCrady teaches that in many cases where a set of wireless devices 14, 16, 18 and 20 are used to identify the location of a mobile device 12, the optimal subset of the wireless devices to be used to identify the mobile

device location will change as the mobile device is moved about within a space. McCrady also teaches that known locations of mobile devices can be used to identify the locations of other mobile devices (i.e., the mobile devices at known locations can be treated as stationary devices for the purpose of determining the location of another mobile device). McCrady further teaches that the optimal subset of mobile devices for determining the location of one mobile device may change as the mobile devices are moved about within a space. Thus, for instance, at a first time when a first mobile device is at a first location, the location of the first mobile device is to be determined and there are five stationary wireless access point devices within transmitting distance of the first mobile device, a subset of three of the stationary devices may be selected as optimal while at a second time when the first mobile device is at the first location and two other mobile devices are within transmitting distance of the first device, a subset including one of the stationary devices and the two other mobile devices may be selected as optimal.

Moreover, referring to McCrady's col. 4, line 56 through col. 5, line 4 and also to col. 8, lines 4-18, McCrady teaches a ranging sequence for determining the distance between two devices wherein the two devices do not have to be precisely synchronized with respect to time. To this end, McCrady teaches that the distance between a first mobile device and a second device where the location of the second device is known can be determined by the first device transmitting an initial ranging message/signal to the second device and storing the time of signal transmission for subsequent use. When the second device receives the initial ranging message, the second device processes the message and sends a return signal back to the first device that indicates the location of the second device along with a time period (i.e., a processing time period) that indicates the duration between when the second device received the initial ranging message and when the second device transmitted the return signal. When the first device receives the return signal, the first device identifies the reception time, identifies the period between initial ranging message transmission and reception of the

return signal as a total communication time, subtracts the processing time period from the total communication time to identify a time of round trip signal flight between the first and second devices and then uses the round trip flight time to determine the distance between the two devices. Where three or more device to device distances are determined, McCrady teaches that a mobile device position estimate can be generated.

Thus, importantly, McCrady only teaches a single method of determining device position and therefore cannot possibly teach a system where two different methods are used to generate two different position estimates where the two estimates are then used to identify a single final estimate.

Also, importantly, while Fullerton teaches several different position estimating processes, Fullerton fails to teach or suggest a method wherein two different processes are performed to generate two different position estimates and where the two estimates are then used to identify a final position estimate.

D. The Prior Art Does not Disclose or Suggest the Claimed Invention

1. Claims 53, 87, 100 and Related Dependent Claims

Claim 53 is written to cover a method wherein (1) a first subset of position information is used to identify a first estimate of WID position, (2) a second subset of position information is used to identify a second estimate of WID position and wherein (3) the first and second estimates are used to identify a final estimate of WID location.

In the final Office Action, the Examiner contends that distance estimates are akin to position estimates. To this end, in the Office Action dated July 28, 2006 at the paragraph numbered "3", the Examiner cites Fullerton's Figs. 11, 12A and 13 as well as paragraphs 38-40 and 115-117 as teaching the steps of using first and second subsets of position information to identify first and second WID position estimates and using the first and second estimates to identify a final position estimate.

Turning to Fullerton's Figs. 11 and 12A and related paragraphs 105 through 111 which corresponds to Fullerton's first and simplest embodiment, that portion of Fullerton describes a system where the position of a mobile radio is determined by estimating a distance between a radio at a known position and the mobile radio, using a directional

antenna to determine the angle or direction between the two radios and then using the angle and the distance estimate to estimate position. Consistent with this understanding see Fullerton's paragraph 112 that states that "Finally, the position (x2, y2) of the object is determined using the distance d and the angular direction ϕ" (emphasis added) and the last sentence in paragraph 14. Paragraphs 38-40 that were also cited by the Examiner are consistent with this first embodiment where one distance and one direction are determined and then used to identify a final position estimate.

Turning to Fullerton's paragraphs 115-117 and Fig. 13, paragraphs 115 and 116 and Fig. 13 describe Fullerton's third embodiment where distances d2 and d3 are determined and used with known radio positions (x1, y1) and (x2, y2) to generate a single position estimate. Consistent with this understanding of Fullerton's third embodiment, Fullerton states that "Finally, in a step 1420, the position (x3, y3) of the object O is calculated from d2, d3, (x1, y1) and (x2, y2) using a triangulation method." (Emphasis added).

Fullerton's paragraph 117 describes Fullerton's fourth embodiment that is similar to the third embodiment wherein three distances d1, d2 and d3 are used via a triangulation process to estimate position of a mobile radio (see last sentence in paragraph 117).

Moreover, in the Response to Argument section that starts of page 16 of the final Office Action the Examiner refers to distances d2 and d3 as positions. Thus, clearly in the final Office Action the Examiner treated distance estimates incorrectly as position estimates.

A distance from a point alone is not a position estimate. If one states that a vehicle is 500 miles from Denver, the distance specification alone does not indicate a position. Similarly, an angle or direction between a first known location and a second location is not a position of the second location. For instance, it is impossible to tell where a vehicle is that is due east of Denver. Instead, as clearly recognized by Fullerton's first and second embodiments, both direction and distance from a known location are required to specify a position. In the above geographic example, if one

states that a vehicle is exactly 500 miles due east of Denver, a position is known from the combined distance and direction information.

Because both direction and distance are required to specify position, one of direction and position cannot alone be considered a position estimate. Thus, while Fullerton's first embodiment teaches separately identifying a distance and a direction, the first embodiment clearly only contemplates generating one position estimate and cannot anticipate claim 53. Similarly, while Fullerton's third and fourth embodiments teach separately identifying several distance estimates, each of the third and fourth embodiments alone only contemplates generating one position estimate and cannot anticipate claim 53.

While Fullerton clearly teaches several different position estimating processes, nothing in Fullerton teaches or even remotely suggests that the different estimating processes could be used in parallel or sequentially to generate different estimates or that different position estimates could be combined or used in some fashion to identify a final estimate. Instead, Fullerton treats the estimating methods disclosed as alternative procedures.

To be thorough, Applicant analyzes Fullerton's second, fifth and sixth embodiments here to show why none of those embodiments anticipates claim 53. To this end, Fullerton's second embodiment described at paragraph 113-114 teaches a method similar to Fullerton's first embodiment except that a universal clock is used so that only a one way signal between first and second radios is required to estimate the location of a mobile radio. Here, importantly, like the first embodiment, the second embodiment calls for generating one distance estimate and a direction and using the distance and direction to estimate position. Once again, a distance estimate alone or a direction estimate alone is not a position estimate and claim 53 is not anticipated by this second embodiment.

In Fullerton's fifth embodiment described at paragraphs 118, a single triangulation method using one set of position information is used to identify two different possible positions for a radio (see paragraph 118, lines 7-10 and Fig. 15 where position ambiguity is described). After the two positions are identified, directional

antennas are used to obtain additional information which is in turn used to determine which of the two possible positions corresponds to the actual position of the mobile radio (see paragraph 118, lines 16-22). Thus, instead of identifying first and second position estimates using first and second information subsets, the fifth embodiment uses one information set to generate two different position estimates. After the two different position estimates have been generated, this fifth embodiment requires additional directional antenna data and uses the antenna data, not the position estimates themselves, to identify one of the two estimates as a final estimate. For at least these reasons claim 53 is not anticipated by Fullerton's fifth embodiment.

In Fullerton's sixth embodiment described in paragraph 119, an additional (e.g., a fourth) radio is provided so that a conventional triangulation method using distance estimates as shown in Fig. 16 can be used to estimate position. Here again distance estimates alone are not the same as position estimates and therefore this sixth embodiment does not anticipate claim 53.

In summary, none of Fullerton's embodiments anticipates claim 53 or any of the claims that depend there from.

With respect to the dependent claims, many of the dependent claims include limitations that are not taught or suggested by Fullerton. For example, claim 54 requires, among other things, the step of generating a confidence factor for each of the first and second estimates where the confidence factors are indicative of the accuracy of the first and second estimates. The portion of Fullerton cited in the final Office Action as teaching confidence factors (i.e., paragraph 110) has nothing to do with confidence factors. A confidence factor is a factor that indicates likelihood that an estimate is accurate (see last two sentences in paragraph 13 of the present specification). Fullerton's paragraph 110 describes a correction factor, not a confidence factor.

More specifically, Fullerton's paragraphs 105 through 110 describe Fullerton's first position estimating process wherein a stationary radio transmits an initial signal to a mobile radio, when the mobile radio receives the signal, the mobile radio processes the signal and then transmits a response to the stationary radio and when the stationary

radio receives the response, the stationary radio uses the total time between the initial signal transmission and reception of the return signal to determine the distance between the two radios. Here, the idea is that the signal velocity through air is known and therefore, if the time of signal travel in one direction between the two radios is known, the distance can be determined by multiplying the time of one directional travel by the known signal velocity.

The total time between the initial signal transmission and reception of the return signal includes three distinct periods. The first period is the period for travel from the stationary radio to the mobile radio. In Fullerton this first period is between times t1 and t2 in Fig. 12A. The second period is the period that elapses between the time when the mobile radio receives the initial signal and the time when the mobile radio transmits the return signal (i.e., a processing period). In Fullerton this second period is between times t2 and t3 in Fig, 12A. The third period is the period for travel of the return signal from the mobile radio to the stationary radio. In Fullerton this third period is between times t3 and t4 in Fig. 12A.

If the duration of the second period (i.e., (t3-t2)) is known, the time of one way signal flight between the two radios can be determined by subtracting the processing time (i.e., the second period) from the total time between the initial signal transmission and reception of the return signal (i.e., (t4-t1)) and then dividing the result by 2 (i.e., the result includes the time of flight of both the initial signal and the return signal so the result has to be divided by 2 to get the time of one way signal flight).

Fullerton recognizes that it may be difficult to manufacture processors that have a uniform processing time (t3-t2) and therefore suggests the calibration process described in paragraph 110. To this end, Fullerton suggests a calibration process whereby a person responsible for calibrating the system estimates and specifies the mobile radio processing time (t3-t2) for use by the stationary radio. Next, a mobile radio is positioned at a known distance (e.g., 20 feet) from the location of the stationary radio and the distance estimating process described above is performed to generate a

distance estimate. If the distance estimate is different than the actual distance between the two radios, the estimated processing time (t3-t2) was inaccurate.

Fullerton contemplates two different ways to compensate for an inaccurate estimate (t3-t2). First, Fullerton contemplates simply adjusting distance estimates by the error in the distance estimate that occurred during the commissioning procedure. Second, Fullerton contemplates that the estimated value (t3-t2) can be adjusted until the distance estimating error during the commissioning procedure is eliminated.

Fullerton's correction factor is not related to a position and instead is related to a distance value. An example of how Fullerton's correction factor is applied is instructive here and can help show the difference between Fullerton's distance correction factor and the position confidence factors required by claim 54. In Fullerton, after a commissioning procedure, assume that a distance correction factor is -5 feet and that during a subsequent position estimating process, an initial distance estimate is 25 feet and an angle estimate is 40 degrees. Here, to determine the position of the mobile radio, first, the correction factor is added to the initial distance estimate to generate a corrected distance estimate of 20 feet. Second, the location of the stationary radio, the corrected distance estimate and the estimated angle are used to identify X and Y coordinates of the mobile radio where the X and Y coordinates are a position estimate (see position of radio 1108 in Fig. 11 that are expressed as (x2, y2). Here, the correction factor is completely unrelated to the X and Y coordinates. In fact, the correction factor is "worked into" and reflected in the position estimate so that there is no way to separately identify the correction factor.

In addition, Fullerton's correction factor is simply a factor that is used to correct distance estimates to compensate for an erroneous estimated processing period (t3-t2) and, in many if not all cases, will not reflect true accuracy of the distance estimate. In this regard, assume again that a correction factor is again -5 feet. In addition, assume that at a first time when industrial machines are in a first set of positions and a mobile radio is in a first location 20 feet from an access point, a first initial distance estimate

between the access point and the radio is 25 feet. Assume that at a second time when the industrial machines are in a second set of positions and the mobile radio is again at the first location, a second initial distance estimate is 20 feet due to the fact that the machines obstruct wireless transmissions to a greater degree when the machines are in the second set of positions. Here, the second initial estimate (i.e., 20 feet which is the actual distance between the access point and the radio) is clearly more accurate than the first initial estimate (i.e., 25 feet) and yet the correction factor is still -5 feet in both cases. Thus, regardless of the phrase used to refer to Fullerton's correction factor, the factor is not indicative of the accuracy of the distance estimate and simply is a factor used to compensate for distance errors due to an inaccurate processing time estimate (t3-t2).

For at least these additional reasons claim 54 is not anticipated by Fullerton.

Each of claims 55, 56 and 58 further limit claim 54 and specifically add limitations that are related to the confidence factors. Because Fullerton fails to teach or suggest confidence factors for position estimates, Fullerton cannot possibly teach or suggest these additional limitations to confidence factors.

With respect to claim 65, Applicant notes that each of Figs. 13 and 15 and accompanying specification teaches multiple transceivers that each generate a distance estimate and where the distance estimates are then combined to generate a single location estimate. Here, as in the discussion above with respect to claim 53, distance estimates are not position estimates and Fullerton only generates a single position estimate despite generating multiple distance estimates. Claim 65 requires N-2 position estimates in addition to the first and second position estimates and therefore is novel over Fullerton for this additional reason.

Claim 67 further requires identifying confidence factors that are not contemplated by Fullerton as described above with respect to claim 54.

Regarding claim 87, claim 87 requires, among other things, the steps of (1) tracking WID location with a first wireless position estimating system to generate a first

position estimate, (2) tracking WID location with a second wireless position estimating system to generate a second position estimate and (3) using the first and second estimates to identify a final WID position estimate.

As discussed above with respect to claim 53, Fullerton's distance estimates are not the same as position estimates and Fullerton clearly fails to even remotely suggest a single method in which first and second position estimates are generated. For this reason alone claim 87 is not anticipated by Fullerton.

In addition, while Fullerton teaches different <u>systems</u> for generating different position estimates as shown in Figs. 11, 13, 15 and 16 and as described in Fullerton's specification, Fullerton teaches the different systems as <u>alternatives</u> as opposed to systems that can be used together to perform a single method to generate intermediate position estimates followed by a final estimate. Thus, for this additional reason, claim 87 and claims that depend there from are not anticipated by Fullerton.

Claims that depend from claim 87 include additional distinguishing limitations. To this end, claim 90 requires that the most accurate of the first and second estimate be used as the final estimate. Fullerton fails to teach or suggest the limitations in claim 90 and therefore claim 90 is not anticipated by Fullerton for this additional reason.

Regarding claim 100, claim 100 requires, among other things, the steps of (1) generating a first position estimate via a first estimating program, (2) generating a second position estimate via a second estimating program and (3) using the first and second estimates to identify a final WID position estimate.

As discussed above with respect to claim 53, Fullerton's distance estimates are not the same as position estimates and Fullerton fails to teach or suggest a single method in which first and second position estimates are generated. For this reason alone claim 100 is not anticipated by Fullerton.

In addition, while Fullerton clearly teaches different <u>programs</u> for generating different position estimates, Fullerton teaches the different programs as <u>alternatives</u> as opposed to programs that can be used together to perform a single process to generate intermediate position estimates followed by a final estimate. Thus, for this additional reason claim 100 and claims that depend there from are not anticipated by Fullerton.

Claims that depend from claim 100 include additional distinguishing limitations. To this end, claim 102 requires confidence factors associated with position estimates. Fullerton fails to teach or suggest confidence factors associated with position estimates and therefore claim 102 is novel over Fullerton for this additional reason.

2. Claims 82, 96, 105 and Related Claims

Claim 82 requires, among other things, attempting to use first and second subsets of position information to identify first and second WID position estimates, rendering the first position estimate accessible to applications when the first estimate is identified and rendering the second position estimate accessible to applications when the first estimate is not identified and when the second estimate is identified. Thus, here, there is a preferred estimate (the first estimate) and the second estimate is only rendered accessible when the first estimate cannot be identified.

As discussed above, Fullerton fails to teach or suggest attempting to generate first and second position estimates. Fullerton teaches a system for identifying the position of an object or a device by identifying a distance of the object from a fixed location and identifying a direction from the fixed location to the object and then using the distance and direction information to identify a single location estimate or by identifying several distances from the object and using the distances to triangulate a single position estimate. A distance alone clearly is not a position estimate. Similarly, a direction alone is not a position estimate.

In addition, Fullerton fails to teach or suggest that one estimate of any type should be preferred to another estimate of any type as required by claim 82 (i.e. one estimate is rendered accessible when identified and the other estimate is only rendered accessible when the one estimate is not identified). In this regard, even if distance and direction estimates in Fullerton were some how construed as being position estimates, Fullerton does not teach or suggest that one of the estimates could be used without the other to determine the position of a device – this is not surprising as, as indicated

above, a position has to require both a direction and a distance from a single location (i.e., the position information must be usable to specify X and Y coordinates).

Turning to McCrady, McCrady teaches that in many cases where a set of wireless devices are used to identify the location of a mobile device, the optimal subset of the wireless devices to be used to identify the mobile device location will change as the mobile device is moved about within a space, that known locations of mobile devices can be used to identify the locations of other mobile devices and that the optimal subset of mobile devices for determining the location of one mobile device may change as other mobile devices are moved about within a space. Thus, for instance, at a first time when a first mobile device is at a first location, the location of the first mobile device is to be determined and there are five stationary wireless access point devices within transmitting distance of the first mobile device, a subset of three of the stationary devices may be selected as optimal while at a second time when the first mobile device is at the first location and two other mobile devices are within transmitting distance of the first device, a subset including one of the stationary devices and the two other mobile devices may be selected as optimal.

The portion (col. 16, lines 28-50) of McCrady cited in the Office Action with respect to claim 82 teaches that, to determine which subset of devices is optimal for determining the location of the first mobile device, the first mobile device first performs a ranging process whereby the first mobile device determines how far away the other devices are within the space. After the ranging process is completed, the first mobile device selects the optimal subset of devices, generally as a function of the distances between the first mobile device and the other devices and then uses a single set of data associated with the optimal device subset to generate a <u>single location estimate</u>.

McCrady's ranging simply roughly determines distances (i.e., within a range – hence the term "ranging") between a first device to be located and other devices in the vicinity of the first device. As described above, <u>a distance or range is not a position estimate</u>.

In addition, McCrady fails to teach a predefined preference between estimates of any type. To this end, even in range values where incorrectly construed as position estimates, McCrady teaches that the optimal set of ranges and associated devices is selected dynamically as a function of the ranges and perhaps other spatial orientations (i.e., two devices may be along the same line of sight – see McCrady's col. 16, lines 44-45). Thus, the claim 82 predefined preferences for the one estimate over the other estimate further distinguishes the claim from McCrady.

For at least the above reasons claim 82 and claims that depend there from are not obvious over Fullerton in view of McCrady.

Claim 83 further requires identifying confidence factors for each of first and second estimates when the first and second estimates are both identified and then identifying the estimate with the highest confidence factor as a final estimate. As described above with respect to claim 54, Fullerton teaches distance correction factors used in an interpolation process and fails to teach or suggest confidence factors that indicate relative position accuracy. For this additional reason Applicant believes claim 83 is distinct over the cited references.

With respect to claim 96, claim 96 requires, among other things, estimating device position using a first estimating program, identifying a confidence factor for the first position estimate, when the confidence factor is high, rendering the estimate accessible and when the confidence factor is low repeating the process using a second position estimating program. As described above, neither Fullerton nor McCrady teach or suggest a process wherein two position estimates are generated in any case. Again, the portions of Fullerton cited in the Office Action that relate to claim 96 teach a distance estimate and a separate direction estimate while McCrady teaches multiple range estimates. Separate direction, distance and range estimates are <u>not</u> position estimates as that phrase is used in claim 96. In addition, neither Fullerton nor McCrady teach or suggest <u>position estimate confidence factors</u>. Moreover, neither of the cited references teaches or suggests a cyclical process whereby different positioning

algorithms are performed after a true position estimate has been generated when the estimate is deemed to be unacceptably accurate.

For at least the above reasons Applicant believes that the cited references do not anticipate claim 96 and claims that depend there from.

With respect to claim 105, claim 105 requires, among other things, attempting to identify first and second different position estimates of a device and, when at least one of the estimates is sufficiently accurate, rendering the likely most accurate estimate accessible as a final estimate. As described above, neither Fullerton nor McCrady teach or suggest a process wherein an attempt is made to generate two position estimates. Again, Fullerton teaches a distance estimate and a separate direction estimate while McCrady teaches multiple range estimates. Separate direction, distance and range estimates are <u>not</u> position estimates as that phrase is used in claim 96. In addition, neither Fullerton nor McCrady teach or suggest determining if an estimate is sufficiently accurate or rendering a likely most accurate estimate accessible.

For at least the above reasons Applicant believes that claim 105 and claims that depend there from are not anticipated by the cited references..

E. The Prior Art When Taken as a Whole Does Not Disclose or Suggest the Claimed Invention

The teachings of the two cited references cannot be combined in any manner to arrive at the present invention. As indicated above, neither of the cited references teaches or suggests a method wherein first and second sets of position information are used to generate first and second position estimates and where the position estimates are used to identify a final position estimate. In addition, neither of the cited references teaches or suggests a single system or program that generates first and second position estimates where the estimates are then used to identify a final estimate. Moreover, neither reference teaches or suggests a method where one position estimate is preferred over other estimates so that the other estimates are not rendered unless

the one estimate cannot be generated. Thus, combining the two references together cannot provide the missing claim requirements.

F. Conclusion

The Examiner's grounds for rejecting claims 53-56, 58-70, 72-92, 96, 97 and 100-106 of the present application appear to stem from an incorrect interpretation of the prior art references cited. Claims 53-56, 58-70, 72-92, 96, 97 and 100-106 clearly distinguish over the cited prior art references, and allowance of all of the pending claims in this application is requested.

Respectfully submitted,

DAVID FARCHMIN

Dated: 1-19-07

By: M. Jaskolski
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I hereby certify that this correspondence is being deposited with the United States Postal Services on the date set forth below as First Class Mail in an envelope addressed to: Mail Stop APPEAL, Commissioner for Patents, P.O. Box 1450, Alexandria VA 22313-1450.

Date of Signature
and Deposit: 1-19-07

Michael A. Jaskolski, Reg. No. 37,551

BEFORE THE BOARD OF PATENT APPEALS AND INTERFERENCES

Applicant:	David W. Farchmin
Serial No.:	10/675,608
Filed:	September 30, 2003
Title:	DISTRIBUTED WIRELESS POSITIONING ENGINE METHOD AND ASSEMBLY
Art Unit:	2688
Examiner:	Dai Phuong
Our Ref.:	110003.00057.03AB222

Mail Stop APPEAL
Commissioner for Patents
PO Box 1450
Alexandria VA 22313-1450

APPEAL BRIEF FEE

Dear Sir:

Applicant hereby authorizes the Commissioner to charge Deposit Account No. 01-0857 in the amount of $500 under 37 C.F.R. 41.20(b)(2) for the filing of the Appeal Brief.

No other fee is believed to be required to enter the accompanying Appeal Brief. However, if an additional fee is required please charge Deposit Account No. 01-0857 in the amount of the fee.

Respectfully submitted,

DAVID FARCHMIN

Dated: 1-19-07

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QBMKE\6030143.1

viii. Claims Appendix

1. (Canceled)

2. (Canceled)

3. (Canceled)

4. (Canceled)

5. (Canceled)

6. (Canceled)

7. (Canceled)

8. (Canceled)

9. (Canceled)

10. (Canceled)

11. (Canceled)

12. (Canceled)

13. (Canceled)

14. (Canceled)

15. (Canceled)

16. (Canceled)

17. (Canceled)

18. (Canceled)

19. (Canceled)

20. (Canceled)

21. (Canceled)

22. (Canceled)

23. (Canceled)

24. (Canceled)

25. (Canceled)

26. (Canceled)

27. (Canceled)

28. (Canceled)

29. (Canceled)

30. (Canceled)

31. (Canceled)

32. (Canceled)

33. (Canceled)

34. (Canceled)

35. (Canceled)

36. (Canceled)

37. (Canceled)

38. (Canceled)

39. (Canceled)

40. (Canceled)

41. (Canceled)

42. (Canceled)

43. (Canceled)

44. (Canceled)

45. (Canceled)

46. (Canceled)

47. (Canceled)

48. (Canceled)

49. (Canceled)

50. (Canceled)

51. (Canceled)

52. (Canceled)

53. (Original) A method for use with a portable wireless information device (WID) within a space, the WID including a transmitter for transmitting wireless WID signals, the method comprising the steps of:

obtaining position information indicative of the distances of signal paths between the WID and specific locations within the space;

using a first sub-set of the position information to identify a first estimate of WID location;

using a second sub-set of the position information to identify a second estimate of WID position; and

using the first and second estimates to identifying a final estimate of the WID location.

54. (Previously Presented) The method of claim 53 wherein the step of using the first and second estimates includes generating a separate and distinct confidence factor for each of the estimates where the confidence factors are indicative of the accuracy of the estimates.

55. (Original) The method of claim 54 wherein the step of using the first and second estimates further includes identifying the estimate having the highest confidence factor as the final estimate.

56. (Original) The method of claim 54 further including the step of identifying first and second regions within the space that are associated with the first and second information sub-sets and wherein the step of generating confidence factors includes determining relative juxtapositions between the estimates and the first and second regions.

57. (Original) The method of claim 56 wherein the first and second regions include first and second central locations, respectively, and, wherein, the step of determining relative juxtapositions includes comparing the estimated locations to the first and second central locations.

58. (Original) The method of claim 54 wherein the step of using the first and second estimates further includes mathematically combining the first and second estimates to provide a final estimate of WID location as a function of the confidence factors.

59. (Original) The method of claim 53 further including rendering at least one of the estimates accessible to applications requiring WID position estimates.

60. (Original) The method of claim 53 wherein the step of obtaining includes providing a separate wireless signal receiver at each of the specific locations, receiving signals from the WID and using the signals to identify the position information.

61. (Original) The method of claim 60 wherein the position information includes signal strength information and wherein the step of using the signals includes determining the signal strengths.

62. (Original) The method of claim 53 wherein the step of obtaining includes providing a separate wireless signal transmitter at each of the specific locations and at least one receiver within the space, transmitting signals from the transmitters to the WID, identifying the position information via the WID and transmitting the position information from the WID to the at least one receiver.

63. (Original) The method of claim 62 wherein the position information is signal strength information.

64. (Original) The method of claim 53 wherein first and second facility regions are associated with the first and second position information sub-sets and wherein the first and second regions overlap.

65. (Original) The method of claim 53 further including the step of using N-2 additional sub-sets of the position information to identify N-2 additional estimates of WID position wherein the step of using the first and second estimates to identify a final estimate of the WID position includes using a sub-set of the first through Nth estimates to identify a final estimate of the WID location.

66. (Original) The method of claim 65 wherein the subset of estimates includes all of the first through Nth estimates.

67. (Original) The method of claim 66 wherein the step of using the first through Nth estimates includes identifying a confidence factor for each of the N estimates.

68. (Original) The method of claim 67 wherein the step of using the first through Nth estimates further includes identifying the estimate having the highest confidence factor as the final estimate.

69. (Original) The method of claim 67 further including the step of identifying N regions within the space that are associated with the first through Nth information sub-sets and wherein the step of generating confidence factors includes determining relative juxtapositions between the estimates and the first through Nth regions.

70. (Original) The method of claim 69 wherein the step of identifying N regions includes identifying regions such that each location within the space is located within at least two separate regions.

71. (Original) The method of claim 69 wherein the first through Nth regions include first through Nth central locations, respectively, and, wherein, the step of

determining relative juxtapositions includes comparing the estimated positions to the first through Nth central locations.

72. (Original) The method of claim 67 wherein the step of using the first though Nth estimates further includes mathematically combining at least a sub-set of the first through Nth estimates to provide a final estimate of WID location as a function of the confidence factors.

73. (Original) The method of claim 53 wherein the steps of using the first and second sub-sets of position information include providing a single processor running first and second programs to determine the first and second locations, respectively.

74. (Original) The method of claim 53 wherein the steps of using the first and second sub-sets of position information include providing first and second processors running the first and second programs to determine the first and second locations, respectively.

75. (Original) The method of claim 53 further including the step of identifying first and second regions within the space that are associated with the first and second information sub-sets and wherein the first and second regions at least in part overlap.

76. (Original) The method of claim 53 wherein the step of using a first sub-set includes running a first program to estimate WID position and the step of using a second sub-set includes running a second program to estimate WID position.

77. (Original) The method of claim 76 wherein the first and second programs are different.

78. (Original) The method of claim 77 wherein the first and second sub-sets are identical.

79. (Original) The method of claim 77 wherein the first and second sub-sets are different.

80. (Original) The method of claim 76 wherein at least the first program includes at least first and second algorithms that are performed as a function of general WID location.

81. (Original) The method of claim 53 wherein the space is a three dimensional space within an automated facility.

82. (Original) A method for use with a portable wireless information device (WID) within a space, the WID including a transmitter for transmitting wireless WID signals, the method for tracking the position of the WID within the space and comprising the steps of:

obtaining position information indicative of the distances of signal paths between the WID and specific locations within the space;

attempting to use a first sub-set of the position information to identify a first estimate of WID location;

attempting to use a second sub-set of the position information to identify a second estimate of the WID location;

when one of the first and second estimates is identified, rendering the one of the first and second estimates accessible by applications requiring WID location; and

when the one of the first and second estimates is not identified and the other of the first and second estimates is identified, rendering the other of the first and second estimates accessible by applications requiring WID location.

83. (Original) The method of claim 82 further including the step of, when both the first and second estimates are identified, identifying a confidence factor for each of the first and second estimates where the confidence factors are indicative of the accuracy of the estimates and identifying the estimate associated with the greatest confidence factor as a final estimate to be rendered accessible.

84. (Original) The method of claim 82 wherein the position information includes signal strength information.

85. (Original) The method of claim 82 wherein the step of obtaining includes providing a separate wireless signal receiver at each of the specific locations, receiving signals from the WID and using the signals to identify the position information.

86. (Original) The method of claim 82 wherein the step of obtaining includes providing a separate wireless signal transmitter at each of the specific locations, transmitting signals from the transmitters to the WID, identifying the position information

via the WID and transmitting the position information from the WID to the at least a first receiver.

87. (Original) A method for use with a portable wireless information device (WID) within a space, the WID including a transmitter for transmitting wireless WID signals, the method for tracking location of the WID within the space and comprising the steps of:

tracking WID location with a first wireless position estimating system to generate a first position estimate;

tracking WID location with a second wireless position estimating system to generate a second position estimate; and

using the first and second estimates to identifying a final WID position estimate.

88. (Original) The method of claim 87 wherein each of the tracking steps includes providing receivers at spaced apart specific locations within the space, receiving wireless signals transmitted by the WID and determining a location related characteristic of the received signals that is indicative of the distances of signal paths between the WID and specific locations of the receivers, the step of tracking WID location with the first system further including using a sub-set of the location related characteristics to generate the first position estimate and the step of tracking WID location with the second system further including using a sub-set of the location related characteristics to generate the second position estimate.

89. (Original) The method of claim 88 wherein the location related characteristics includes signal strength.

90. (Original) The method of claim 87 wherein the step of using the first and second estimates to identifying a final WID position estimate includes identifying the most accurate estimate of the first and second estimates as the final estimate.

91. (Original) The method of claim 90 wherein the space is an enclosed space within a facility.

92. (Original) The method of claim 87 wherein the first and second estimating systems use different algorithms to estimate WID position.

93. (Canceled)

94. (Canceled)

95. (Canceled)

96. (Original) A method for estimating the position of a wireless information device (WID) within a space, the method comprising the steps of:

a) estimating WID position via a first estimating program;

b) identifying a confidence factor for the WID position estimate;

c) when the confidence factor meets a threshold requirement, rendering the position estimate accessible to other application; and

d) when the confidence factor fails to meet a threshold requirement, repeating steps (a) through (c) with a second estimating program.

97. (Original) The method of claim 96 wherein step (d) is performed for each of a plurality of estimating programs until one of WID position has been estimated at least once via each of the estimating programs and an estimate that meets the threshold requirement has been identified.

98. (Original) The method of claim 97 wherein, after WID position has been estimated via each of the estimating programs, when none of the estimates meets the threshold requirements, the method includes the step of performing another function.

99. (Original) The method of claim 98 wherein the another function includes indicating that WID position is unknown.

100. (Original) A method for estimating the position of a wireless information device (WID) within a space, the method comprising the steps of:

a) generating a first WID position estimate via a first estimating program;

b) generating a second WID position estimate via a second estimating program; and

c) using the first and second estimates to identify a final WID position estimate.

101. (Original) The method of claim 100 wherein the first and second estimating programs are different.

102. (Original) The method of claim 100 further including the step of generating a confidence factor for each of the first and second estimates and wherein the step of using the first and second estimates includes using to confidence factors.

103. (Original) The method of claim 102 wherein the step of using the confidence factors includes mathematically combining the first and second estimates as a function of the confidence factors.

104. (Original) The method of claim 102 wherein the step of using the confidence factors includes the step of selecting the one of the first and second estimates that is associated with the highest confidence factor as the final estimate.

105. (Original) A method for use with a portable wireless information device (WID) within a space, the WID including a transmitter for transmitting wireless WID signals, the method of tracking the position of the WID within the space and comprising the steps of:

obtaining position information indicative of the distances of signal paths between the WID and specific locations within the space;

attempting to use a first sub-set of the position information to identify a first estimate of WID location;

attempting to use a second sub-set of the position information to identify a second estimate of the WID location;

determining if at least one of the estimates is sufficiently accurate;

when at least one of the estimates is sufficiently accurate, rendering the likely most accurate of the estimates accessible as the final estimate; and

when none of the estimates is sufficiently accurate, performing another function.

106. (Previously Presented) The method of claim 105 wherein the step of performing another function includes indicating that the WID position is unknown.

107. (Previously Presented) The method of claim 105 wherein the step of determining if at least one of the estimates is sufficiently accurate includes generating a confidence factor for each of the estimates and comparing the confidence factor to a threshold factor and, when a confidence factor is greater than the threshold factor, determining that the associated estimate is sufficiently accurate.

ix. Evidence Appendix

US 20030197643A1

(19) United States

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Fullerton et al. (43) Pub. Date: Oct. 23, 2003

(54) SYSTEM AND METHOD FOR POSITION DETERMINATION BY IMPULSE RADIO

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(21) Appl. No.: 10/441,078

(22) Filed: May 20, 2003

Related U.S. Application Data

(60) Continuation of application No. 09/954,204, filed on Sep. 18, 2001, now Pat. No. 6,611,234, which is a continuation of application No. 09/517,161, filed on Apr. 5, 2000, now Pat. No. 6,297,773, which is a division of application No. 09/045,929, filed on Mar. 23, 1998, now Pat. No. 6,133,876.

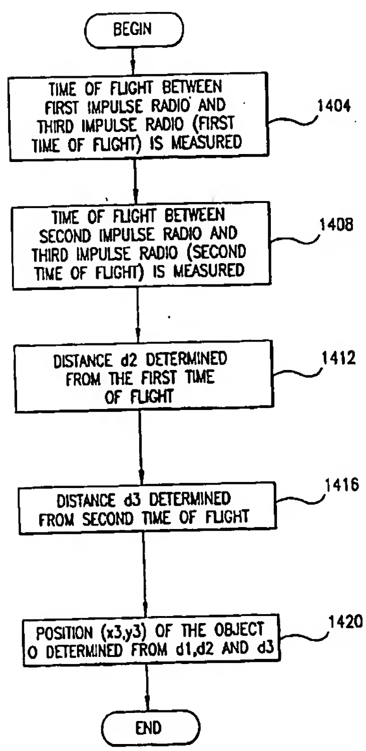
Publication Classification

(51) Int. Cl.[7] G01S 1/24; G01S 3/02

(52) U.S. Cl. 342/387; 342/458

(57) ABSTRACT

A system and a method for position determination by impulse radio using a first transceiver having a first clock providing a first reference signal and a second transceiver placed spaced from the first transceiver. The system determines the position of the second transceiver. The second transceiver has a second clock that provides a second reference signal. A first sequence of pulses are transmitted from the first transceiver. The first sequence of pulses are then received at the second transceiver and the second transceiver is then synchronized with the first sequence of pulses. A second sequence of pulses are transmitted from the second transceiver. The first transceiver receives the second sequence of pulses and the first transceiver is synchronized with the second sequence of pulses. A delayed first reference signal is generated in response to the synchronization with the second sequence of pulses. A time difference between the delayed first reference signal and the first reference signal is then measured. The time difference indicates a total time of flight of the first and second sequence of pulses. The distance between the first and the second transceiver is determined from the time difference. The direction of the second transceiver from the first transceiver is determined using a directional antenna. Finally, the position of the second transceiver is determined using the distance and the direction.



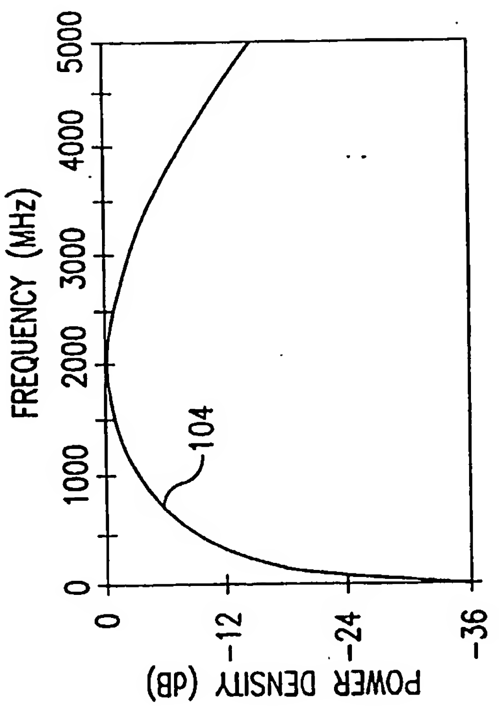

FREQUENCY (MHz)
0
1000
2000
3000
4000
5000
104
0
-12
-24
-36
POWER DENSITY (dB)

FIG.1B

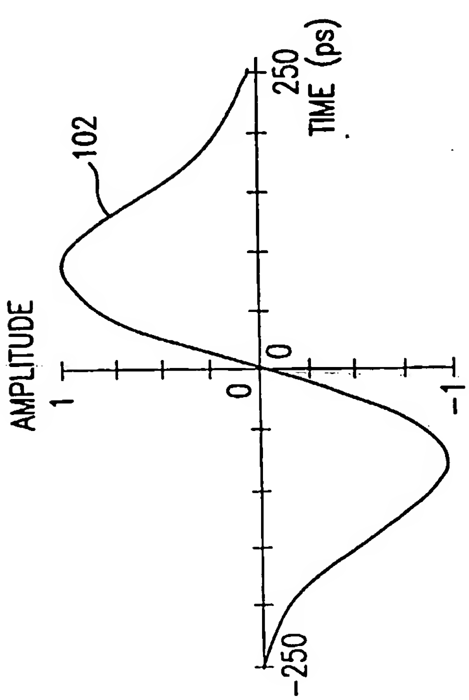

AMPLITUDE
1
0
-1
102
0
-250
250
TIME (ps)

FIG.1A

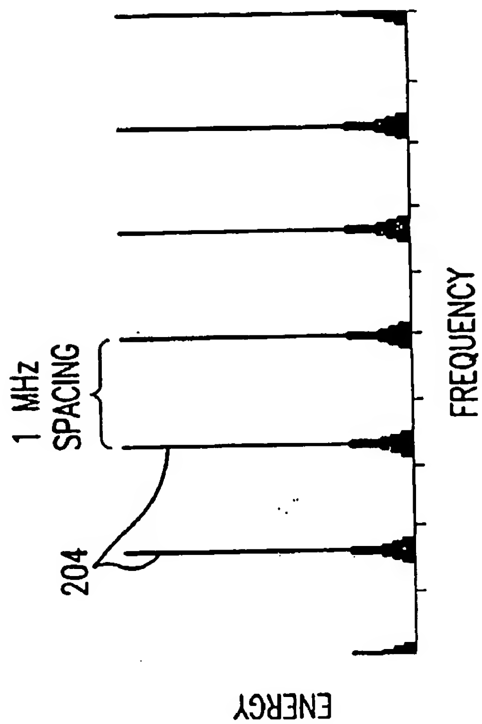


FIG.2B

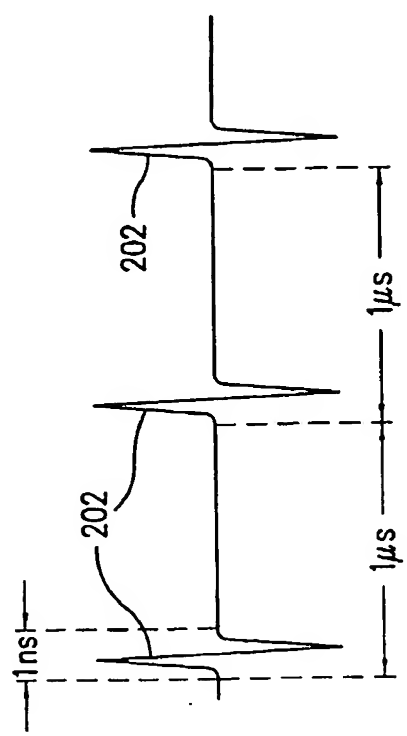


FIG.2A

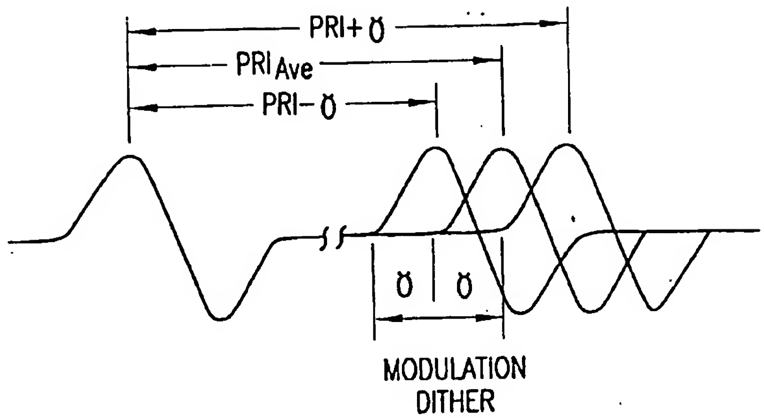

PRI+ δ
PRI Ave
PRI− δ
δ
δ
MODULATION
DITHER

FIG.3

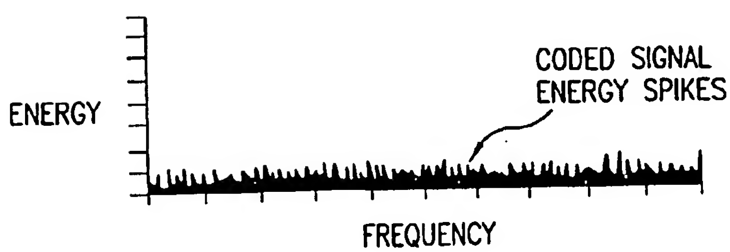

ENERGY
CODED SIGNAL
ENERGY SPIKES
FREQUENCY

FIG.4

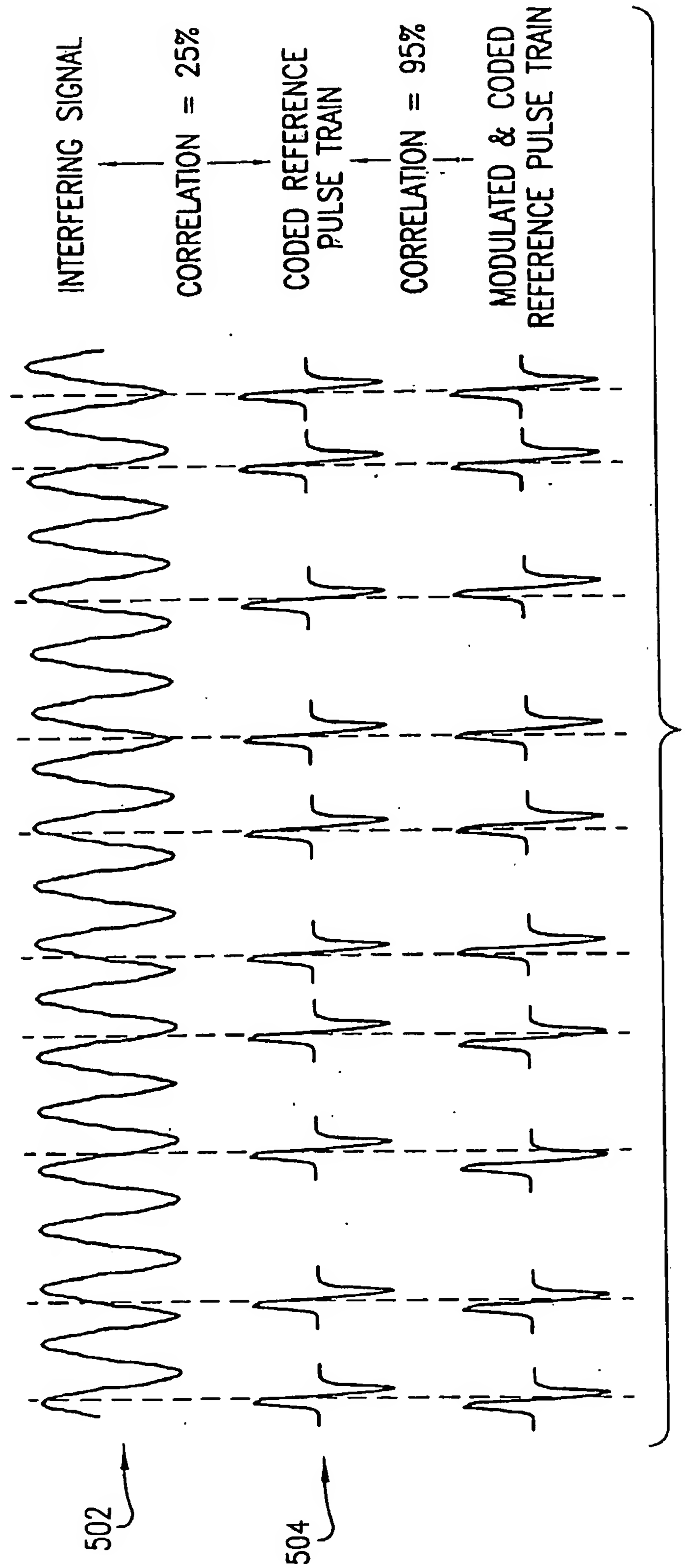

INTERFERING SIGNAL
CORRELATION = 25%
CODED REFERENCE PULSE TRAIN
CORRELATION = 95%
MODULATED & CODED REFERENCE PULSE TRAIN
502
504

FIG.5

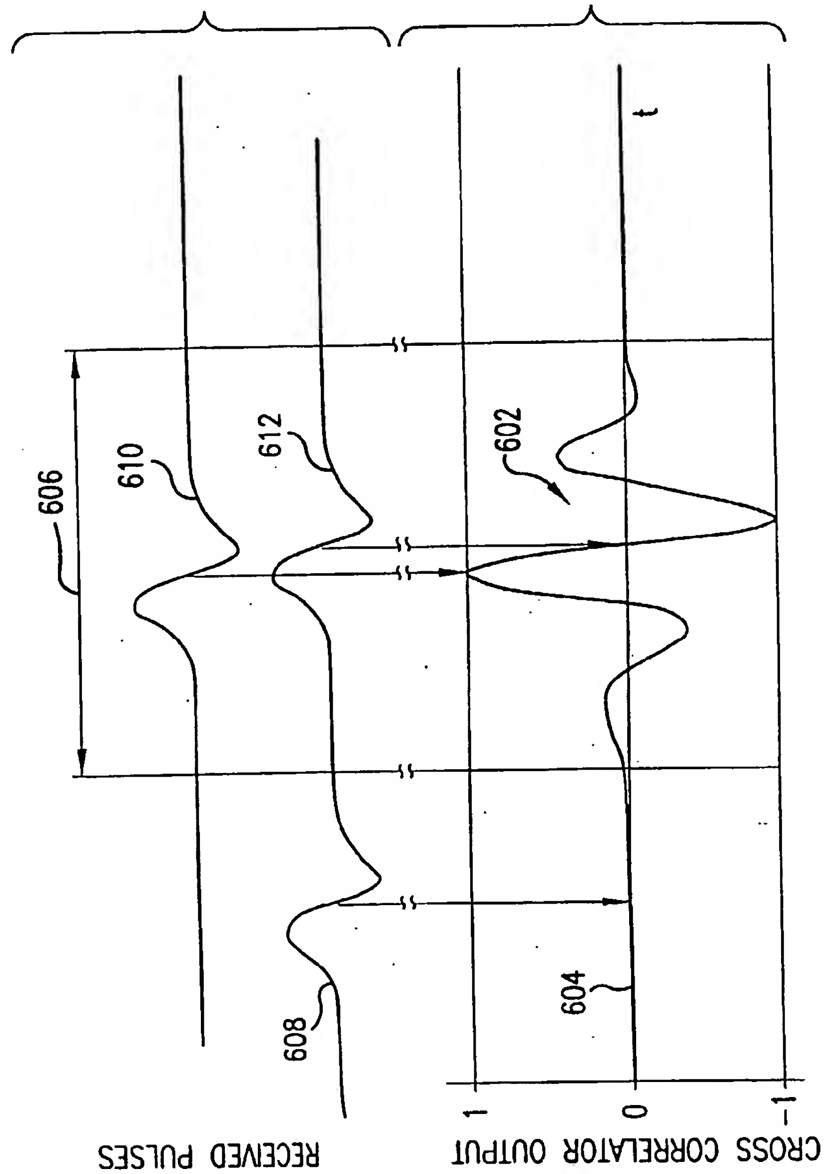

RECEIVED PULSES
CROSS CORRELATOR OUTPUT
606
610
612
602
604
608
1
0
-1
t

FIG.6A

FIG.6B

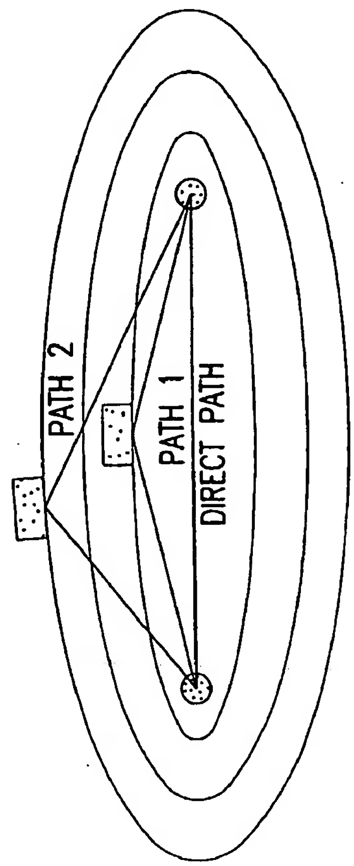

PATH 2
PATH 1
DIRECT PATH

FIG.7A

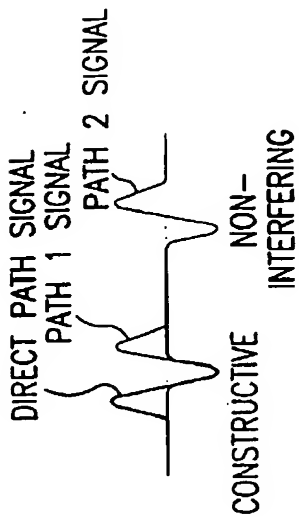

DIRECT PATH SIGNAL
PATH 1 SIGNAL
PATH 2 SIGNAL
CONSTRUCTIVE
NON-INTERFERING

FIG.7B

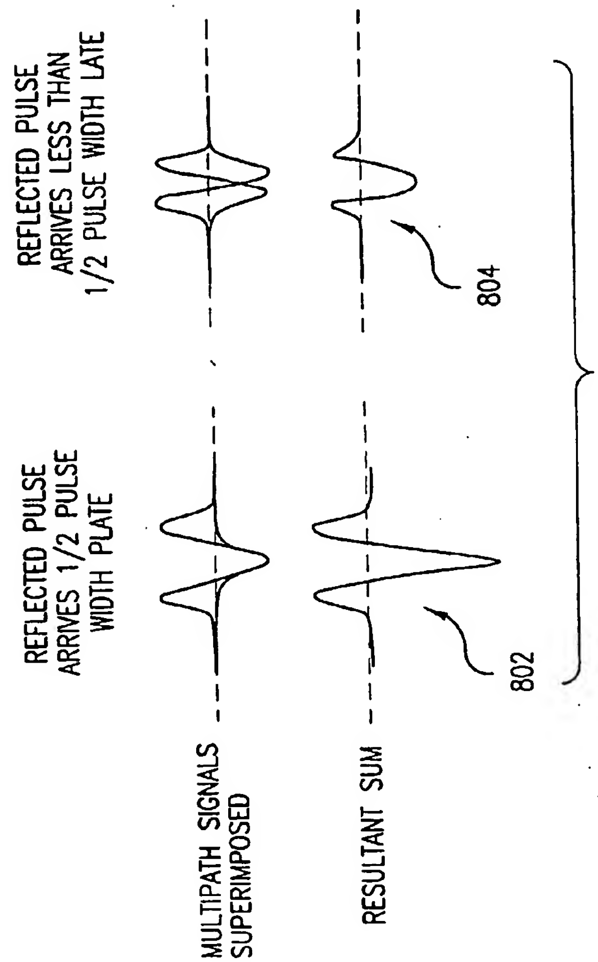

REFLECTED PULSE ARRIVES 1/2 PULSE WIDTH PLATE
REFLECTED PULSE ARRIVES LESS THAN 1/2 PULSE WIDTH LATE
MULTIPATH SIGNALS SUPERIMPOSED
RESULTANT SUM
802
804

FIG.8

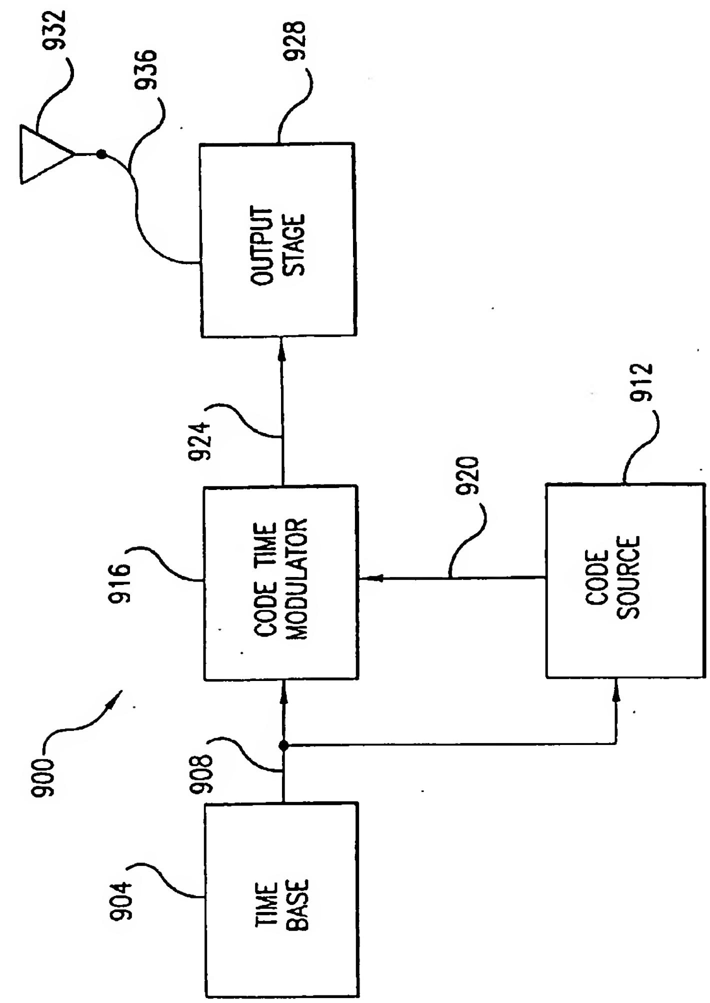

900
904
TIME BASE
908
912
CODE SOURCE
916
CODE TIME MODULATOR
920
924
928
OUTPUT STAGE
932
936

FIG.9

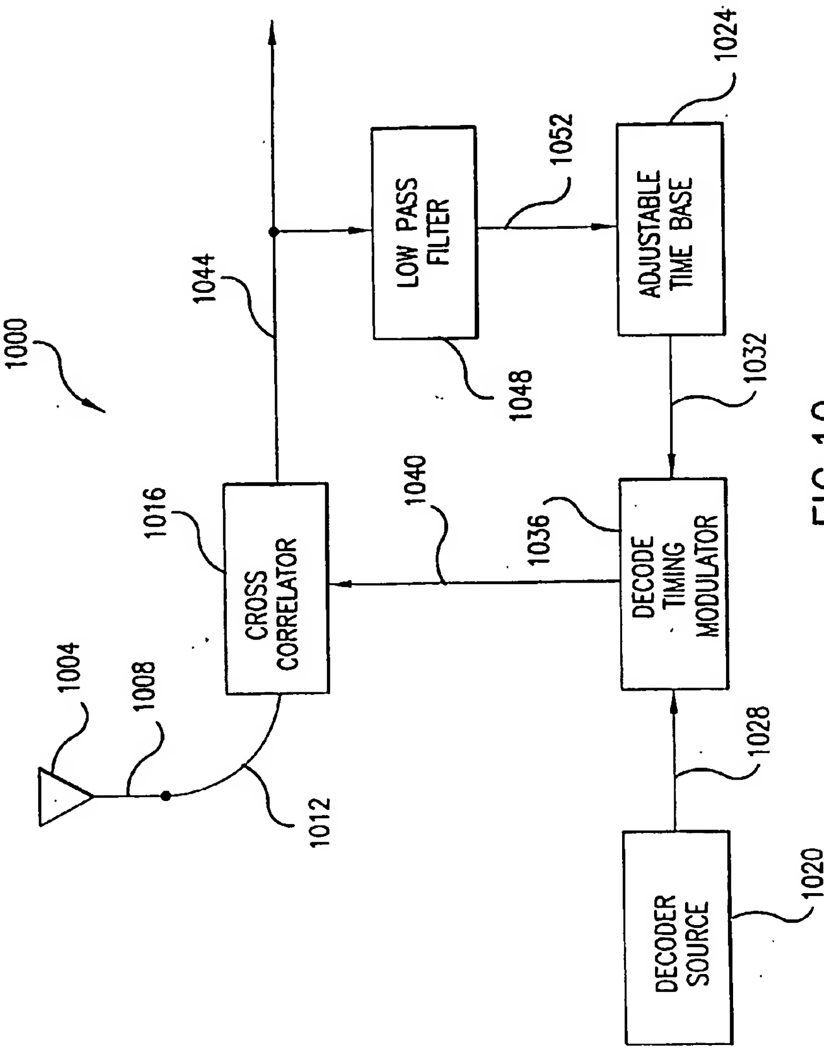

1000
1004
1008
1012
1016
CROSS CORRELATOR
1044
LOW PASS FILTER
1048
1052
ADJUSTABLE TIME BASE
1024
1032
1040
1036
DECODE TIMING MODULATOR
1028
DECODER SOURCE
1020

FIG.10

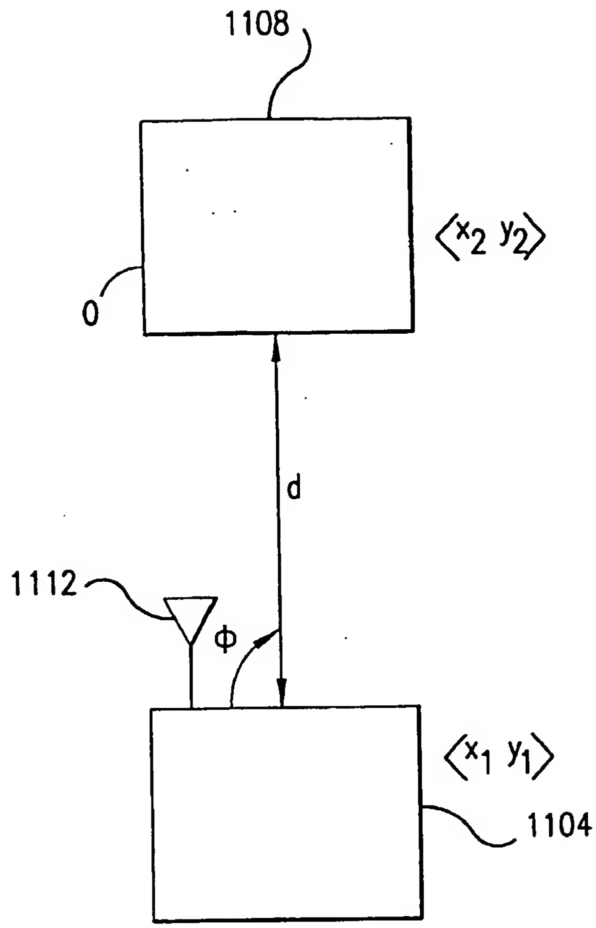
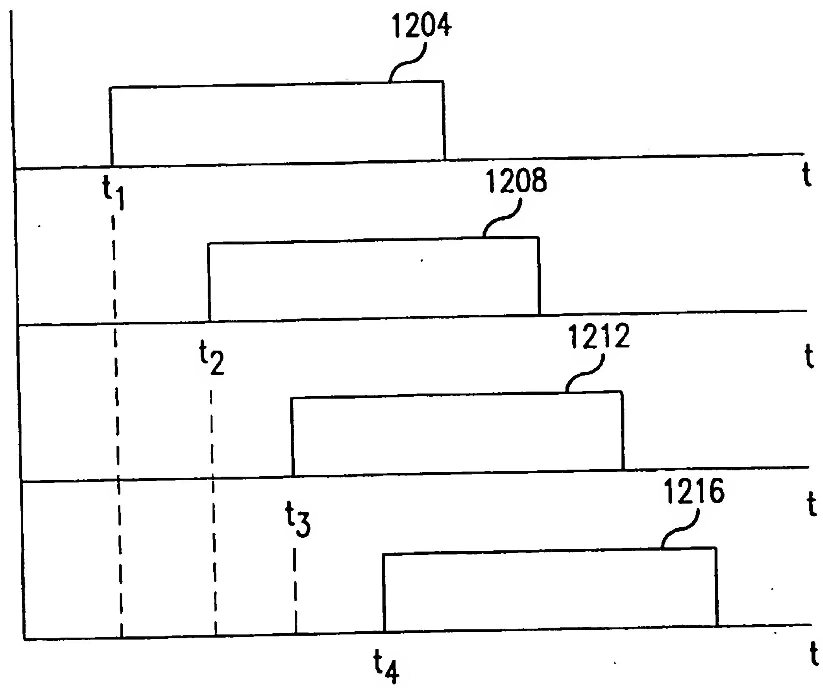


FIG.11



ACTUAL TIME OF FLIGHT=$(t_4-t_1)-(t_3-t_2)$

FIG.12A

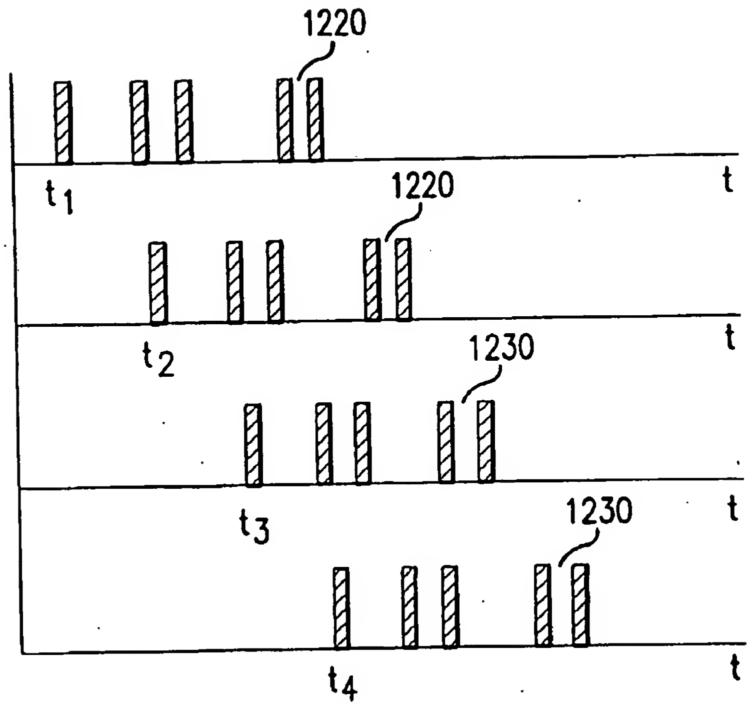


FIG.12B

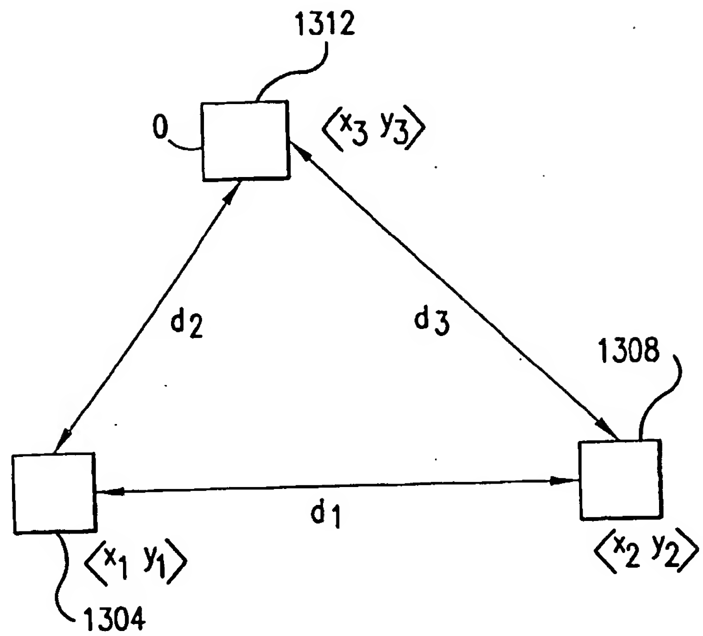


FIG.13

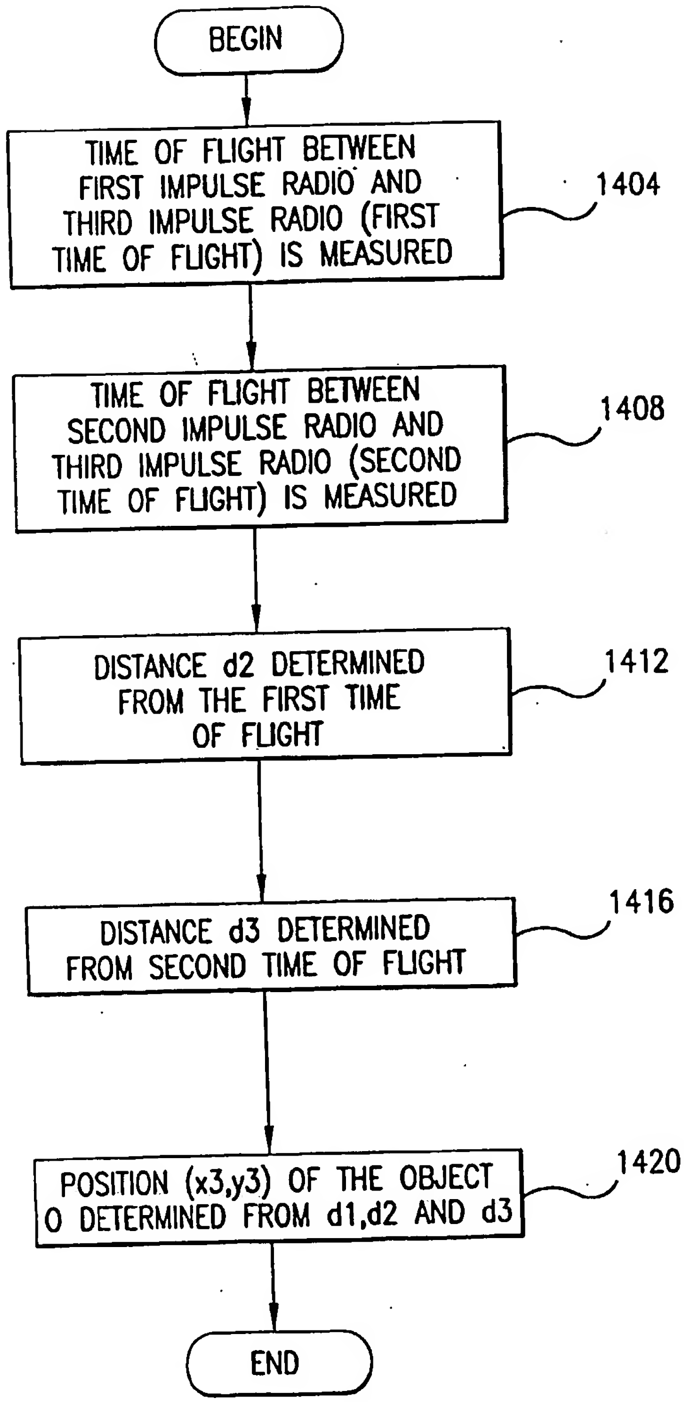

BEGIN
TIME OF FLIGHT BETWEEN FIRST IMPULSE RADIO AND THIRD IMPULSE RADIO (FIRST TIME OF FLIGHT) IS MEASURED
1404
TIME OF FLIGHT BETWEEN SECOND IMPULSE RADIO AND THIRD IMPULSE RADIO (SECOND TIME OF FLIGHT) IS MEASURED
1408
DISTANCE d2 DETERMINED FROM THE FIRST TIME OF FLIGHT
1412
DISTANCE d3 DETERMINED FROM SECOND TIME OF FLIGHT
1416
POSITION (x3,y3) OF THE OBJECT O DETERMINED FROM d1,d2 AND d3
1420
END

FIG.14

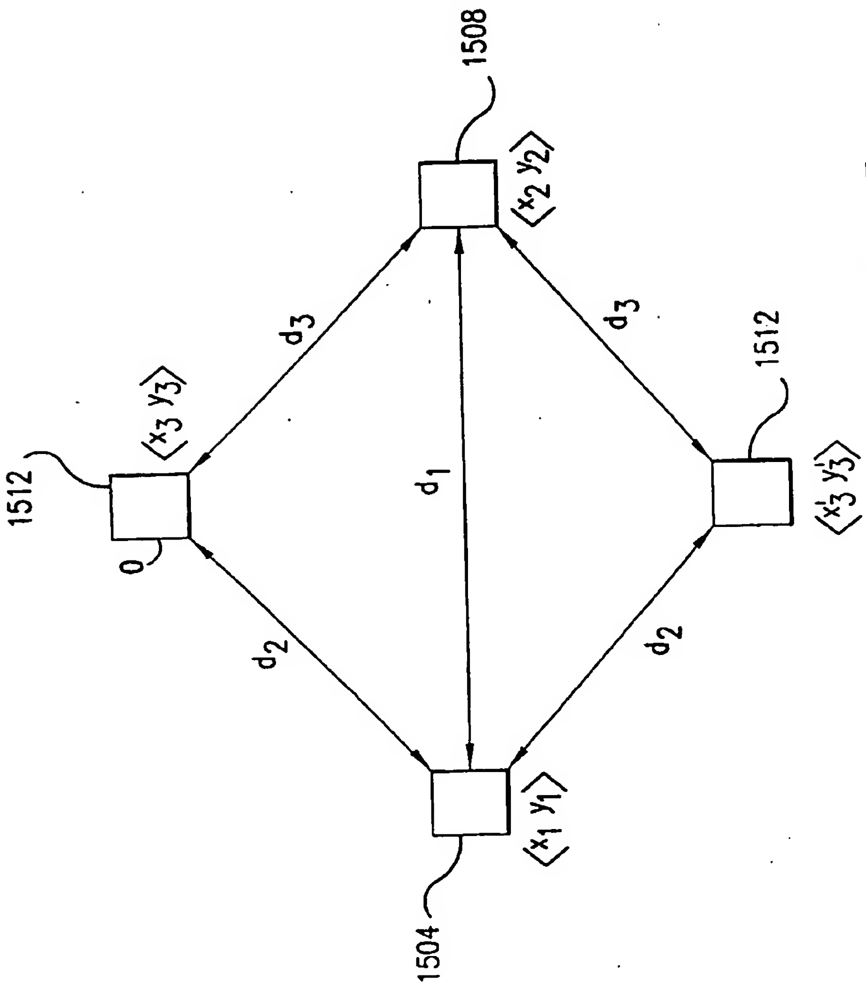

1508
1512
1512
1504
0
d1
d2
d2
d3
d3
$\langle x_2\ y_2 \rangle$
$\langle x_3\ y_3 \rangle$
$\langle x'_3\ y'_3 \rangle$
$\langle x_1\ y_1 \rangle$

FIG.15

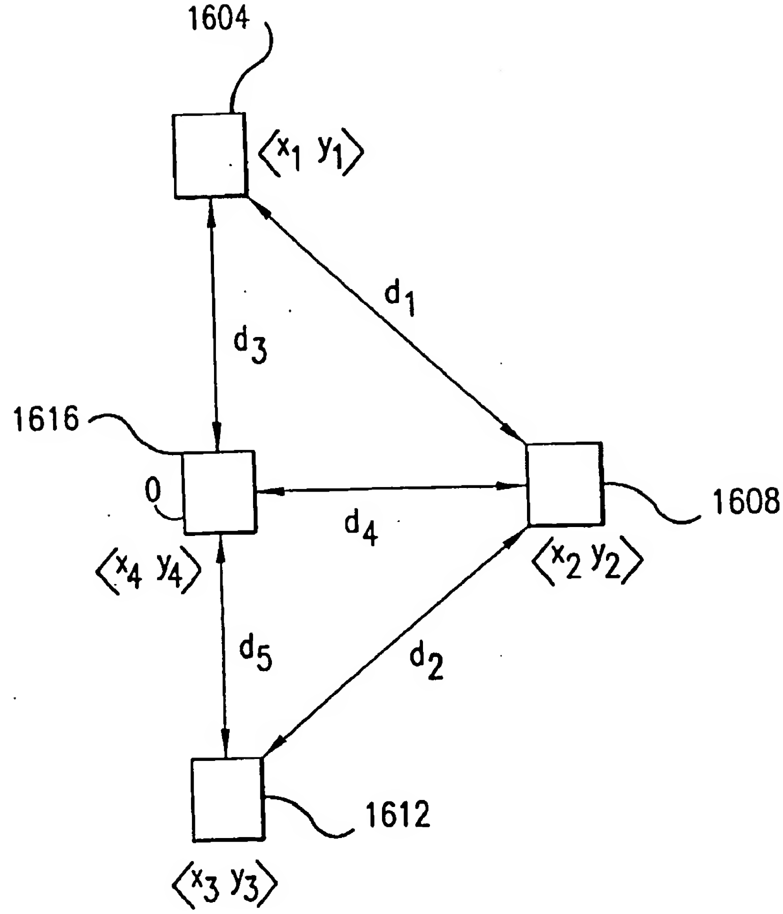

1604
$\langle x_1\ y_1 \rangle$
d_1
d_3
1616
0
d_4
1608
$\langle x_4\ y_4 \rangle$
$\langle x_2\ y_2 \rangle$
d_5
d_2
1612
$\langle x_3\ y_3 \rangle$

FIG.16

SYSTEM AND METHOD FOR POSITION DETERMINATION BY IMPULSE RADIO

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This is a continuation of application Ser. No. 09/517,161, filed Apr. 5, 2000, which is a divisional of application Ser. No. 09/045,929, filed Mar. 23, 1998 (now U.S. Pat. No. 6,133,876, issued Oct. 17, 2000).

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention generally relates to position determination, and more specifically to a system and method for position determination by impulse radio.

[0004] 2. Background Art

[0005] In recent years, modern communications technology has provided various systems for position determination. The global positioning system (GPS) operated by the United States Department of Defense, for example, is a highly complex system of determining the position of an object. The GPS system depends on measuring the time-of-flight of microwave signals from three or more orbiting satellite transmitters by a navigation receiver that computes the position of the mobile unit. According to the GPS system, each satellite broadcasts a time-stamped signal that includes the satellite's ephemeris, i.e., its own position. When the mobile unit receives a GPS signal, the mobile unit measures the transmission delay relative to its own clock and determines the pseudo-range to the transmitting satellite's position. The GPS system requires three satellites for two-dimensional positioning, and a fourth satellite for three-dimensional positioning.

[0006] Another approach is that employed by the U.S. Navy's TRANSIT system. In that system, a mobile unit performs continuous doppler measurements of a signal broadcast by a low earth orbit (LEO) satellite. The measurements continue for several minutes. The system usually requires two passes of the satellite, necessitating a wait of more than 100 minutes. In addition, because the position calculations are performed by the mobile unit, the satellite must broadcast information regarding its position, i.e., its ephemeris. Although the TRANSIT system is capable of high accuracy (on the order of one meter), the delay required is unacceptable for commercial applications.

[0007] Although these systems accurately determine the unknown position of an object, they are extremely complex, and, more importantly, expensive to implement. For example, both the GPS and TRANSIT systems require multiple satellites, sophisticated receivers and antennas that require hundreds of millions dollars of investments. Also, response times of GPS and TRANSIT systems are typically slow due to their narrow bandwidth. Furthermore, since these systems depend on orbiting satellites, they require an unimpeded view of the sky to operate effectively.

[0008] There is a great need in many different fields for a simple, less expensive alternative to complicated position determination systems. One such area is a typical shipping terminal, e.g., a major sea-port or an airport. In a sea-port, containers having valuable cargo are stored at warehouses or are left in designated places in the terminals. Also, containers are sometimes moved from one section of the port to another section in preparation for their eventual loading into a cargo ship or being picked up by trucks or railcars after being unloaded from a cargo ship. Often it is necessary to determine the location of one or more containers. However, it is difficult to identify one or more containers among hundreds, or thousands of containers in a terminal. Similar problems are also encountered in airports and railway terminals where containers are kept in storage sites.

[0009] A simple, less expensive position determination system is also desirable for locating police units. Such a position determination system can be used as a vehicle locator system. A city dispatcher would be able to quickly and efficiently dispatch police units if the dispatcher has pre-existing knowledge of each unit's locations. Currently city dispatchers use mobile phones to communicate with police units in order to know their locations. However, using mobile phones to determine the positions of the police units has some disadvantages. Use of mobile phones is expensive and time consuming. Also, when a police officer is not in the car, it is not possible to determine the unit's location.

[0010] Recently, the FCC has mandated that all cell phone systems implement position determination for use in emergency call location. In addition, there is a need for position determination as part of cell phone security, fraudulent use, and zone handoff algorithms. These requirements are difficult to meet and GPS is not adequate to reliably deliver the required accuracy.

[0011] For these reasons, it is clear that there is a need for a simple, low cost position determination system.

BRIEF SUMMARY OF THE INVENTION

[0012] The present invention is directed to a system and a method for position determination using impulse radios. According to one embodiment of the present invention, a first transceiver having a first clock providing a first reference signal is positioned. A second transceiver whose position is to be determined is spatially displaced from the first transceiver. The second transceiver has a second clock that provides a second reference signal.

[0013] To determine the position of the second transceiver, a first sequence of pulses are transmitted from the first transceiver. The first sequence of pulses are then received at the second transceiver and the second transceiver is then synchronized with the first sequence of pulses. Then, a second sequence of pulses are transmitted from the second transceiver. The first transceiver receives the second sequence of pulses and the first transceiver is synchronized with the second sequence of pulses. A delayed first reference signal is generated in response to the synchronization with the second sequence of pulses. Then, a time difference between the delayed first reference signal and the first reference signal is measured. The time difference indicates a total time of flight of the first and second sequence of pulses.

[0014] Then, the distance between the first and the second transceiver is determined from the time difference. Then, the direction of the second transceiver from the first transceiver is determined using a directional antenna. Finally, the position of the second transceiver is determined using the distance and the direction.

[0015] In another embodiment of the present invention a plurality of first transceivers and a second transceiver are placed such that each transceiver is spaced from the others. The distance between each first transceiver and the second transceiver is measured. Then, the position of the second transceiver is determined using a triangulation method.

[0016] In yet another embodiment of the present invention, the second transceiver is placed in a mobile telephone whose position is to be determined. This allows a user of a mobile telephone to determine his or her exact location.

[0017] The position determination system according to the present invention provides numerous advantages over conventional position determination systems described before. For example, the present invention does not require the use of expensive orbiting satellites. Thus, the present invention is less expensive to implement. Also, signals from orbiting satellites are often impeded by obstacles, such as trees or overhead structures. Since, the present invention does not require the use of orbiting satellites, the operation of the present invention is not impeded by obstacles, such as trees or other structures. Furthermore, since the present invention utilizes ultra-wideband signals, it provides a relatively fast response time. As a result, the position of an object can be determined much faster than it would be possible using existing systems.

[0018] Further features and advantages of the present invention, as well as the structure and operation of various embodiments of the present invention, are described in detail below with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The present invention is described with reference to the accompanying drawings. In the drawings, like reference numbers indicate identical or functionally similar elements. Additionally, the left-most digit(s) of a reference number identifies the drawing in which the reference number first appears.

[0020] **FIGS. 1A and 1B** show a 2 GHz center frequency monocycle pulse in the time and frequency domains, respectively, in accordance with the present invention.

[0021] **FIGS. 2A and 2B** are illustrations of a 1 mpps system with 1 ns pulses in the time and frequency domains, respectively, in accordance with the present invention.

[0022] **FIG. 3** illustrates a modulating signal that changes the pulse repetition interval (PRI) in proportion to the modulation in accordance with the present invention.

[0023] **FIG. 4** is a plot illustrating the impact of pseudorandom dither on energy distribution in the frequency domain in accordance with the present invention.

[0024] **FIG. 5** illustrates the result of a narrowband sinusoidal (interference) signal overlaying an impulse radio signal in accordance with the present invention.

[0025] **FIGS. 6A and 6B** show received pulses at a cross correlator and output signal at the cross correlator, respectively.

[0026] **FIGS. 7A and 7B** illustrate impulse radio multipath effects in accordance with the present invention.

[0027] **FIG. 8** illustrates the phase of the multipath pulse in accordance with the present invention.

[0028] **FIG. 9** illustrates one embodiment of an impulse radio transmitter according the present invention.

[0029] **FIG. 10** illustrates one embodiment of an impulse radio receiver according o the present invention.

[0030] **FIG. 11** illustrates one embodiment of the present invention comprising two impulse radios and a direction finding antenna.

[0031] **FIGS. 12A and 12B** are timing diagrams illustrating the operation of the embodiment of **FIG. 11**.

[0032] **FIG. 13** shows another embodiment of the present invention comprising three impulse radios.

[0033] **FIG. 14** is an operational flow diagram illustrating the steps involved in **FIG. 13**.

[0034] **FIG. 15** illustrates a phenomenon known as position ambiguity.

[0035] **FIG. 16** illustrates yet another embodiment of the present invention that resolves the position ambiguity of **FIG. 15**.

DETAILED DESCRIPTION OF THE INVENTION

[0036] Overview of the Invention

[0037] The present invention is directed to a system and a method for position determination using impulse radios. Impulse radio was first fully described in a series of patents, including U.S. Pat. Nos. 4,641,317 (issued Feb. 3, 1987), 4,813,057 (issued Mar. 14, 1989), 4,979,186 (issued Dec. 18, 1990) and 5,363,108 (issued Nov. 8, 1994) to Larry W. Fullerton. A second generation of impulse radio patents include U.S. Pat. Nos. 5,677,927 (issued Oct. 14, 1997), 5,687,169 (issued Nov. 11, 1997) and co-pending application Ser. No. 08/761,602 (filed Dec. 6, 1996) to Fullerton et al. These patent documents are incorporated herein by reference.

[0038] Prior to a detailed description of the present invention, a high level explanation of the invention is provided. According to one embodiment of the present invention, a first transceiver having a first clock providing a first reference signal is positioned. A second transceiver whose position is to be determined is placed spaced from the first transceiver. The second transceiver has a second clock that provides a second reference signal.

[0039] A first sequence of pulses are transmitted from the first transceiver. The first sequence of pulses are then received at the second transceiver and the second transceiver is then synchronized with the first sequence of pulses. Next, a second sequence of pulses are transmitted from the second transceiver. The first transceiver receives the second sequence of pulses and the first transceiver is synchronized with the second sequence of pulses. Next, a delayed first reference signal is generated in response to the synchronization with the second sequence of pulses. Next, a time difference between the delayed first reference signal and the first reference signal is measured. The time difference indicates a total time of flight of the first and second sequence of pulses.

[0040] Next, the distance between the first and the second transceiver is determined from the time difference. Then, the direction of the second transceiver from the first transceiver is determined using a direction finding antenna. Finally, the position of the second transceiver is determined using the distance and the direction.

[0041] In another embodiment of the present invention, the second transceiver is placed in a mobile telephone whose position is to be determined. This allows a mobile telephone network to determine a user's exact location. Additional embodiments are described in detail below in the section titled "Position Determination by Impulse Radio."

[0042] Impulse Radio Basics

[0043] Impulse radio refers to a radio system based on a waveform that is essentially the impulse response of the available bandwidth. An ideal impulse radio waveform is a short Gaussian monocycle. As the name suggests, this waveform attempts to approach one cycle of RF energy at a desired center frequency. Due to implementation and other spectral limitations, this waveform may be altered significantly in practice for a given application. Most waveforms with enough bandwidth approximate a Gaussian shape to a useful degree.

[0044] Impulse radio can use many types of modulation, including AM, time shift (also referred to as pulse position) and M-ary versions. The time shift method has simplicity and power output advantages that make it desirable. In this document, the time shift method is used as an illustrative example.

[0045] In impulse radio communications, the pulse-to-pulse interval is varied on a pulse-by-pulse basis by two components: an information component and a pseudo-random code component. Generally, spread spectrum systems make use of pseudo-random codes to spread the normally narrow band information signal over a relatively wide band of frequencies. A spread spectrum receiver correlates these signals to retrieve the original information signal. Unlike direct sequence spread spectrum systems, the pseudo-random code for impulse radio communications is not necessary for energy spreading because the monocycle pulses themselves have an inherently wide bandwidth. Instead, the pseudo-random code is used for channelization, energy smoothing in the frequency domain, jamming resistance and reducing the signature of a signal to an intercept receiver.

[0046] The impulse radio receiver is typically a homodyne receiver with a cross correlator front end in which the front end coherently converts an electromagnetic pulse train of monocycle pulses to a baseband signal in a single stage. The baseband signal is the basic information channel for the basic impulse radio communications system, and is also referred to as the information bandwidth. It is often found desirable to include a subcarrier with the base signal to help reduce the effects of amplifier drift and low frequency noise. The subcarrier that is typically implemented alternately reverses modulation according to a known pattern at a rate faster than the data rate. This pattern is reversed again just before detection to restore the original data pattern. This method permits AC coupling of stages, or equivalent signal processing to eliminate DC drift and errors from the detection process. This method is described in detail in U.S. Pat. No. 5,677,927 to Fullerton et al.

[0047] The data rate of the impulse radio transmission is only a fraction of the periodic timing signal used as a time base. Each data bit typically time position modulates many pulses of the periodic timing signal. This yields a modulated, coded timing signal that comprises a train of identically shaped pulses for each single data bit. The cross correlator of the impulse radio receiver integrates multiple pulses to recover the transmitted information.

[0048] Waveform

[0049] Impulse radio refers to a radio system based on a waveform that approaches the impulse response of the available bandwidth. In the widest bandwidth embodiment, the resulting waveform approaches one cycle per pulse at the center frequency. In more narrow band embodiments, each pulse consists of a burst of cycles usually with some spectral shaping to control the bandwidth to meet desired properties such as out of band emissions or in-band spectral flatness, or time domain peak power or burst off time attenuation.

[0050] In the course of system analysis and design, it is convenient to model the desired waveform in an ideal sense to provide insight into the optimum behavior for detail design guidance. One such waveform model that has been useful is the Gaussian monocycle as shown in **FIG. 1A**. This waveform is representative of the transmitted pulse produced by a step function into an ultra-wideband antenna. The basic equation normalized to a peak value of 1 is as follows:

$$f_{mono}(t) = \sqrt{e}\left(\frac{t}{\sigma}\right)e^{\frac{-t^2}{2\sigma^2}}$$

[0051] where σ is a time scaling parameter,

[0052] t is time,

[0053] $f_{mono}(t)$ is the waveform voltage, and

[0054] e is the natural logarithm base.

[0055] The frequency domain spectrum of the above waveform is shown in **FIG. 1B**. The corresponding equation is:

$$F_{mono}(f) = (2\pi)^{\frac{3}{2}}\sigma f e^{-2(\pi\sigma f)^2}$$

[0056] The center frequency (f_c), or frequency of peak spectral density is:

$$f_c = \frac{1}{2\pi\sigma}$$

[0057] These pulses, or burst of cycles, may be produced by methods described in the patents referenced above or by other methods that are known to one of ordinary skill in the art. Any practical implementation will deviate from the ideal mathematical model by some amount, which may be considerable since impulse radio systems can tolerate seemingly considerable deviation with acceptable system conse-

quences. This is especially true in the microwave implementations where precise waveform shaping is difficult to achieve.

[0058] These mathematical models are provided as an aid to describing the ideal operation and are not intended to limit the invention. In fact, any burst of cycles that adequately fills a given bandwidth and has an adequate on-off attenuation ratio for a given application will serve the purpose of this invention.

[0059] One of the great advantages of measuring distances and locating positions using this waveform is that the pulse is short enough for individual cycles to be identified so that ambiguity is removed and distance can be resolved to better than a cycle given adequate signal to noise ratio. This can be done by locking onto the signal at incremental cycle points and noting which one has the greatest amplitude. This lock point will be the main lock point and can be used to calibrate the system.

[0060] A Pulse Train

[0061] Although one or more bit per pulse systems have been conceived, impulse radio systems typically use pulse trains, not single pulses, for communications. As described in detail below, the impulse radio transmitter produces and outputs a train of pulses for each bit of information.

[0062] Prototypes built by the inventors have pulse repetition frequencies of between 0.7 and 10 megapulse per second (mpps, where each megapulse is 10^6 pulses). **FIGS. 2A and 2B** are illustrations of a 1 mpps system with (uncoded, unmodulated) 1 nanosecond (ns) pulses in the time and frequency domains (see **102** and **104**, respectively). In the frequency domain, this highly regular pulse train produces energy spikes (comb lines **204**) at one megahertz intervals; thus, the already low power is spread among the comb lines **204**. This pulse train carries no information and, because of the regularity of the energy spikes, might interfere with conventional radio systems at short ranges.

[0063] Impulse radio systems typically have very low duty cycles so the average power in time domain is significantly lower than its peak power in the time domain. In the example in **FIGS. 2A and 2B**, the impulse transmitter operates 0.1% of the time (i.e., 1 ns per microsecond (μs)).

[0064] Additional processing is needed to modulate the pulse train so that the impulse radio system can actually communicate information. The additional processing also smooths the energy distribution in the frequency domain so that impulse radio transmissions (e.g., signals) interfere minimally with conventional radio systems.

[0065] Modulation

[0066] Any aspect of the waveform can be modulated to convey information. Amplitude modulation, phase modulation, frequency modulation, time shift modulation and M-ary versions of these have been proposed. Both analog and digital forms have been implemented. Of these, digital time shift modulation has been demonstrated to have various advantages and can be easily implemented using a correlation receiver architecture.

[0067] Digital time shift modulation can be implemented by shifting the coded time position by an additional amount δ. With this method, the modulation shift is very small relative to the code shift. In a 10 mpps system with a center frequency of 2 GHz, for example, the coded pulse position may be anywhere within 100 ns, but any given pulse would be specified to be at its assigned position within 30 picoseconds (ps). The modulation would deviate this position by 75 ps, early or late, to represent a 1 or a 0 at that level of coding. Note that this is typically not the final data level of coding, but a pseudo Manchester subcarrier level of coding.

[0068] Thus, a train of n pulses is each delayed a different amount from its respective time base clock position by a code delay amount plus a modulation amount, where n is the number of pulses associated with a given data symbol digital bit.

[0069] Coding for Energy Smoothing and Channelization

[0070] Because the receiver is a cross correlator, the amount of time position modulation required for one-hundred percent modulation is calculated by $1/(4f_c)$ (where f_c is the center frequency). For a monocycle with a center frequency of 2.0 GHz, for example, this corresponds to ±125 (ps) of time position modulation. The spectrum-smoothing effects at this level of time dither is negligible.

[0071] Impulse radio achieves optimal smoothing by applying to each pulse a pseudo-random noise (PN) code dither with a much larger magnitude than the modulation dither. **FIG. 4** is a plot illustrating the impact of PN code dither on energy distribution in the frequency domain. **FIG. 4**, when compared to **FIG. 2B**, shows the impact of using a 256 position PN code relative to an uncoded signal.

[0072] PN code dithering also provides for multi-user channelization (channelization is a technique employed to divide a communications path into a number of channels). In an uncoded system, differentiating between separate transmitters would be very hard. The PN codes create channels, if the PN codes themselves are relatively orthogonal (i.e., there is low correlation and/or interference between the codes being used).

[0073] Reception and Demodulation

[0074] Clearly, if there were a large number of impulse radio users within a confined area, there might be mutual interference. Further, while the PN coding minimizes that interference, as the number of users rises, the probability of an individual pulse from one user's sequence being received simultaneously with a pulse from another user's sequence increases. Fortunately, implementations of an impulse radio according to the present invention do not depend on receiving every pulse. The impulse radio receiver performs a correlating, synchronous receiving function (at the RF level) that uses a statistical sampling of many pulses to recover the transmitted information.

[0075] Impulse radio receivers typically integrate 100 or more pulses to yield the demodulated output. The optimal number of pulses over which the receiver integrates is dependent on a number of variables, including pulse rate, bit rate, jamming levels, and range.

[0076] Jam Resistance

[0077] Besides channelization and energy smoothing, the PN coding also makes impulse radio highly resistant to jamming from all radio communications systems, including other impulse radio transmitters. This is critical as any other

signals within the band occupied by an impulse signal act as a jammer to the impulse radio. Since there are no unallocated bands available for impulse systems, they must share spectrum with other conventional radios without being adversely affected. The PN code helps impulse systems discriminate between the intended impulse transmission and interfering transmissions from others.

[0078] **FIG. 5** illustrates the result of a narrowband sinusoidal jamming (interference) signal **502** overlaying an impulse radio signal **504**. At the impulse radio receiver, the input to the cross correlator would include that narrowband signal **502**, as well as the received ultrawide-band impulse radio signal **504**. Without PN coding, the cross correlator would sample the jamming signal **502** with such regularity that the jamming signals could cause significant interference to the impulse radio receiver. However, when the transmitted impulse signal is encoded with the PN code dither (and the impulse radio receiver is synchronized with that identical PN code dither) it samples the jamming signals randomly. According to the present invention, integrating over many pulses negates the impact of jamming. In statistical terms, the pseudo-randomization in time of the receive process creates a stream of randomly distributed values with a mean of zero (for jamming signals).

[0079] Processing Gain

[0080] Impulse radio is jam resistant because of its large processing gain. For typical spread spectrum systems, the definition of processing gain, which quantifies the decrease in channel interference when wide-band communications are used, is the ratio of the bandwidth of the channel to the bandwidth of the information signal. For example, a direct sequence spread spectrum system with a 10 kHz information bandwidth and a 16 MHz channel bandwidth yields a processing gain of 1600 or 32 dB. However, far greater processing gains are achieved with impulse radio systems where for the same 10 KHz information bandwidth and a 2 GHz channel bandwidth the processing gain is 200,000 or 53 dB.

[0081] The duty cycle (e.g., of 0.5%) yields a process gain of 23 dB. (The process gain is generally the ratio of the bandwidth of a received signal to the bandwidth of the received information signal.) The effective oversampling from integrating multiple pulses to recover the information (e.g., integrating 200 pulses) yields a process gain of 23 dB. Thus, a 2 GHz divided by a 10 mpps link transmitting 50 kilobits per second (kbps) would have a process gain of 46 dB, (i.e., 0.5 ns pulse width divided by a 100 ns pulse repetition interval would have a 0.5% duty cycle, and 10 mps divided by a 50,000 bps would have 200 pulses per bit.)

[0082] Capacity

[0083] Theoretical analyses suggest that impulse radio systems can have thousands of voice channels. To understand the capacity of an impulse radio system one must carefully examine the performance of the cross correlator. **FIG. 6B** shows the "cross correlator transfer function"**602**. This represents the output value of an impulse radio receiver cross correlator as a function of received pulse timing. As illustrated at **604**, the cross correlator's output is zero volts when pulses arrive outside of a cross correlation window **606**. As pulse arrival time varies along the time axis of **FIG. 6A**, the corresponding correlator output integral varies according to **FIG. 6B**. It is at its maximum (e.g., 1 volt) when the pulse is $\tau/4$ ahead of the center of the window (as shown at **610**), zero volts when centered in the window (as shown at **612**); and at its minimum (e.g., −1 volt) when it is $\tau/4$ after the center.

[0084] When the system is synchronized with the intended transmitter, the cross correlator's output has a swing of maximum value, e.g., between ±1 volt (as a function of the transmitter's modulation). Other in-band transmission would cause a variance to the cross correlator's output value. This variance is a random variable and can be modeled as a Gaussian white noise signal with a mean value of zero. As the number of interferers increases the variance increases linearly. By integrating over a large number of pulses, the receiver develops an estimate of the transmitted signal's modulation value. Thus, the:

$$\text{Variance of the Estimate} = \frac{N\sigma^2}{\sqrt{Z}} \qquad (1)$$

[0085] Where N=number of interferers, σ^2 is the variance of all the interferers to a single cross correlation, and Z is the number of pulses over which the receiver integrates to recover the modulation.

[0086] This is a good relationship for a communications system for as the number of simultaneous users increases, the link quality degrades gradually (rather than suddenly).

[0087] Multipath and Propagation

[0088] Multipath fading, the bane of sinusoidal systems, is much less of a problem (i.e., orders of magnitude less) for impulse systems than for conventional radio systems. In fact Rayleigh fading, so noticeable in cellular communications, is a continuous wave phenomenon, not an impulse communications phenomenon.

[0089] In an impulse radio system in order for there to be multipath effects, special conditions must persist. The path length traveled by the scattered pulse must be less than the pulse's width times the speed of light, and/or successively emitted pulses at the transmitter (in the sequence) arrive at the receiver at the same time.

[0090] For the former with a one nanosecond pulse, that equals 0.3 meters or about 1 foot (i.e., 1 ns×300,000,000 meters/second). (See **FIG. 7**, in the case where the pulse traveling "Path 1" arrives one half a pulse width after the direct path pulse.)

[0091] For the latter with a 1 megapulse per second system that would be equal to traveling an extra 300, 600 or 900 meters. However, because each individual pulse is subject to the pseudo-random dither, these pulses are decorrelated.

[0092] Pulses traveling between these intervals do not cause self-interference (in **FIG. 7**, this is illustrated by the pulse traveling Path 2). While pulses traveling grazing paths, as illustrated in **FIG. 7** by the narrowest ellipsoid, create impulse radio multipath effects.

[0093] As illustrated in **FIG. 8** at **802**, if the multipath pulse travels one half width of a pulse width further, it increases the power level of the received signal (the phase of

the multipath pulse will be inverted by the reflecting surface). If the pulse travels less than one half a pulse width further it will create destructive interference, as shown at 804. For a 1 ns pulse, for example, destructive interference will occur if the multipath pulse travels between about 0 and 15 cm (0 and 6 inches).

[0094] Position Determination By Impulse Radio

[0095] Although, the advantages of the impulse radio technology have been demonstrated in voice and data communication, an additional area that can benefit from the impulse radio technology is position determination. The impulse radio technology can be advantageously utilized to determine the position of an object, and it can provide a less expensive, simpler alternative to the GPS and the TRANSIT systems discussed earlier.

[0096] The present invention is a system and a method for position determination by impulse radio technology. The preferred embodiments of the invention are discussed in detail below. While specific steps, configurations and arrangements are discussed, it should be understood that this is done for illustrative purposes only. A person skilled in the relevant art will recognize that other steps, configurations and arrangements can be used without departing from the spirit and scope of the present invention.

[0097] **FIG. 9** illustrates an embodiment of an impulse radio transmitter **900** according to the present invention that can be used in position determination. Referring now to **FIG. 9**, transmitter comprises a time base **904** that generates a periodic timing signal **908**. The time base **904** comprises a voltage controlled oscillator, or the like, which is typically locked to a crystal reference, having a high timing accuracy. The periodic timing signal **908** is supplied to a code source **912** and a code time modulator **916**.

[0098] The code source **912** comprises a shift register, a computational device or a storage device such as a random access memory (RAM), read only memory (ROM), or the like, for storing codes and outputting the codes as code signal **920**. In one embodiment of the present invention, orthogonal PN codes are stored in the code source **912**. The code source **912** monitors the periodic timing signal **908** to permit the code signal to be synchronized to the code time modulator **916**. The code time modulator **916** uses the code signal **920** to modulate the periodic timing signal **908** for channelization and smoothing of the final emitted signal. The output of the code time modulator **916** is called a coded timing signal **924**.

[0099] The coded timing signal **924** is provided to an output stage **928** that uses the coded timing signal as a trigger to generate pulses. The pulses are sent to a transmit antenna **932** via a transmission line **936** coupled thereto. The pulses are converted into propagating electromagnetic waves by the transmit antenna **932**. The electromagnetic waves propagate to an impulse radio receiver (shown in **FIG. 10**) through a propagation medium, such as air.

[0100] **FIG. 10** illustrates an impulse radio receiver **1000** according to one embodiment of the present invention that can be used in position determination. Referring now to **FIG. 10**, the impulse radio receiver **1000** comprises a receive antenna **1004** for receiving a propagating electromagnetic wave and converting it to an electrical signal, referred herein as the received signal **1008**. The received signal is provided to a cross correlator **1016** via a transmission line **1012** coupled to the receive antenna **1004**.

[0101] The receiver **1000** comprises a decode source **1020** and an adjustable time base **1024**. The decode source **1020** generates a decode signal **1028** corresponding to the code used by the associated transmitter **900** that transmitted the propagated signal. The adjustable time base **1024** generates a periodic timing signal **1032** that comprises a train of template signal pulses having waveforms substantially equivalent to each pulse of the received signal **1008**.

[0102] The decode signal **1028** and the periodic timing signal **1032** are received by the decode timing modulator **1036**. The decode timing modulator **1036** uses the decode signal **1028** to position in time the periodic timing signal **1032** to generate a decode control signal **1040**. The decode control signal **1040** is thus matched in time to the known code of the transmitter **900** so that the received signal **1008** can be detected in the cross correlator **1016**.

[0103] The output **1044** of the cross correlator **1016** results from the cross multiplication of the input pulse **1008** and the signal **1040** and the integration of the resulting signal. This is the correlation process. The signal **1044** is filtered by a low pass filter **1048** and a signal **1052** is generated at the output of the low pass filter **1048**. The signal **1052** is used to control the adjustable time base **1024** to lock onto the received signal. The signal **1052** corresponds to the average value of the cross correlator output, and is the lock loop error signal that is used to control the adjustable time base **1024** to maintain a stable lock on the signal. If the received pulse train is slightly early, the output of the low pass filter **1048** will be slightly high and generate a time base correction to shift the adjustable time base slightly earlier to match the incoming pulse train. In this way, the receiver is held in stable relationship with the incoming pulse train. Further impulse radio receiver and transmitter embodiments are described in the U.S. Pat. Nos. 5,677,927 and 5,687,169 patents noted above.

[0104] FIGS. 11-16 illustrate system level diagrams of several embodiments of the present invention using one or more impulse radios.

[0105] **FIG. 11** illustrates the present invention in its simplified form, wherein first and second impulse radios **1104** and **1108** and a direction finding antenna **1112** are used to determine the position of an object O.

[0106] The impulse radios **1104** and **1108** are each configured to provide the functionalities of both a transmitter and a receiver. The first impulse radio **1104** and the direction finding antenna are at a location (x1, y1). The second impulse radio **1108** is mounted on the object O whose position (x2, y2) is to be determined. The object O is located at a distance d from the first impulse radio **1104**. Note that with all of the embodiments of this invention where the receiver or the transmitter is mounted on the object O or a reference point, it is not necessary to mount the antenna **1112** at such point.

[0107] **FIGS. 12A and 12B** are timing diagrams illustrating the operation of the embodiment of **FIG. 11**. For the sake of simplicity, the operation of the present invention is illustrated using a reference clock pulse (**FIG. 12A**) in conjunction with pulse trains (**FIG. 12B**). In actual operation, a sequence of reference clock pulses are generated by

clocks at the impulse radios **1104** and **1108**. The reference clock pulses are then processed by the impulse radios and are used to generate to pulse trains shown in **FIG. 12B**. The shape of the actual transmitted waveform is shown in **FIG. 2A**.

[0108] Referring now to **FIG. 12A**, a reference clock pulse **1204** is generated by the impulse radio **1104** at time t_1. The reference clock pulse **1204** corresponds to the transmission of a pulse train **1220** by the impulse radio **1104**. (Also at time t_1, a pulse train **1220** is transmitted by the impulse radio **1104**.) The pulse train **1220** is received by the impulse radio **1108** at time t_2, at which time the impulse radio **1108** synchronizes its own clock with the pulse train **1220**. A reference clock pulse **1208** generated by the impulse radio **1108** corresponds to the synchronization of the impulse radio **1108** with the pulse train **1220**.

[0109] Next, at time t_3, the impulse radio **1108** transmits a pulse train **1230**. A reference clock pulse **1212** generated by the impulse radio **1108** at time t_3 corresponds to the transmission of the pulse train **1230**. Thus, t_3-t_2 is the elapsed time between when the impulse radio **1108** receives the pulse train **1220** and the time the impulse radio **1108** transmits the pulse train **1230**. The pulse train **1230** is received by the impulse radio **1104** at time t_4 at which time the impulse radio **1104** synchronizes itself with the pulse train **1230**. A reference clock pulse **1216** generated by the impulse radio **1104** at time t_4 corresponds to the impulse radio **1104** synchronizing itself with the pulse train **1230**.

[0110] Next, the time difference between the reference clock pulse **1216** and the reference clock pulse **1204** is determined. The time difference is given by t_4-t_1. The time difference represents the elapsed time between the transmission of the pulse train **1220** by the impulse radio **1104** and the reception of the pulse train **1230** by the impulse radio **1104**. The time of flight is given by $(t_4\text{-}t_1)-(t_3\text{-}t_2)$, where $(t_3\text{-}t_2)$ is the delay encountered at the impulse radio **1108**. The time $(t_3\text{-}t_2)$ can be resolved by a system calibration step where the transceivers are set up at known distances and an estimated time representing $(t_3\text{-}t_2)$ is used to calculate distance. Any error becomes a correction factor to be subtracted from all subsequent distance measurements, or alternatively the estimated time representing $(t_3\text{-}t_2)$ can be updated to show the correct distance and the updated time used for subsequent distance calculations

[0111] Next, the distance d is calculated from the time of flight. Then, the angular direction ϕ of the impulse radio **1108** is determined by the direction finding antenna **1112**. The angular direction ϕ of the impulse radio **1108** is the angle of the impulse radio **1108** with respect to the first impulse radio **1104**.

[0112] Finally, the position (x2, y2) of the object O is determined using the distance d and the angular direction ϕ.

[0113] In another embodiment of the present invention, further simplification and cost reduction is achieved by using a passive receiver method. According to the passive receiver method, the impulse radio **1104** is configured solely as a receiver, while the impulse radio **1108** is configured solely as a transmitter. The impulse radios **1104** and **1108** are synchronized by a universal clock, i.e. an external clock or an atomic clock. In other words, internal clocks (or voltage controlled oscillators (VCOs)) of the impulse radios **1104** and **1108** are in sync with an external clock, i.e., a universal clock. This insures that the internal clocks (or VCOs) of the impulse radio run synchronously. The synchronization can be achieved by initializing clocks prior to the impulse radios being deployed into operation. The details of such synchronization would be apparent to a person skilled in the relevant art.

[0114] In operation, at time t_1, impulse radios **1104** and **1108** each generate a reference clock pulse T1. Also, at time t_1, the impulse radio **1108** transmits a sequence of pulses (S_1). S_1 is received by the impulse radio **1104**. The impulse radio **1104** then synchronizes itself with S_1 and produces a delayed reference clock pulse T1'. The impulse radio **1104** then determines the time difference (T1'−T1). The impulse radio **1104** then calculates the position (x2, y2) according to the technique described above.

[0115] In yet another embodiment of the present invention, a third impulse radio can be substituted in lieu of the direction finding antenna for position determination. **FIG. 13** shows an embodiment of the present invention having three impulse radios **1304**, **1308** and **1312**. The first and the second impulse radio **1304** and **1308** are located at positions (x1, y1) and (x2, y2), respectively, each spaced from the other by a distance d_1. The third impulse radio **1312** is mounted on the object O whose position (x3, y3) is to be determined. The object O is located at distances d_2 and d_3 from the first and the second impulse radio **1304** and **1308**, respectively.

[0116] **FIG. 14** is an operational flow diagram illustrating the method of determining the position of the object O in accordance with the embodiment of **FIG. 13**. In a step **1404**, the time of flight (also referred to as the first time of flight) between the first impulse radio **1304** and the third impulse radio **1312** is determined. In a step **1408**, the time of flight (also referred to as the second time of flight) between the second impulse radio **1308** and the third impulse radio **1312** is determined. In a step **1412**, the distance d_2 is determined from the first time of flight. In a step **1416**, the distance d_3 is determined from the second time of flight. Finally, in a step **1420**, the position (x3, y3) of the object O is calculated from d_2, d_3, (x1, y1) and (x2, y2) using a triangulation method. The distance d_1 can be measured and provides a check on the relative coordinates (x1, y1) and (x2, y2). This information and any error can be used to update the measurement system.

[0117] Again, further simplification and cost reduction of the embodiment of **FIG. 13** can be achieved by using a passive receiver method. According to the passive receiver method, the first and the second impulse radio **1304** and **1308** are each configured solely as a receiver, while the third impulse radio **1312** is configured solely as a transmitter. The first, second and third impulse radios **1304**, **1308** and **1312** are synchronized by a universal clock. The synchronization of the clocks can be achieved by initializing the clocks prior to the impulse radios being deployed into operation. Other synchronization techniques can be employed as would be apparent to a person skilled in the relevant art. In operation, the distances d_2 and d_3 are measured using methods described earlier. Then, the position of the object (x3, y3) is determined from d_1, d_2 and d_3 by a triangulation method.

[0118] The use of only three impulse radios results in a phenomenon known as position ambiguity, which is illus-

trated in **FIG. 15**. Briefly stated, position ambiguity refers to the condition wherein a triangulation method provides two solutions for the position of the object. One solution is the actual position (x3, y3) of the object, while the other solution (x3', y3') is a mirror image of the actual position. Referring now to **FIG. 15**, a triangulation method provides a solution that indicates that the object may be located at either (x3, y3) or at (x3', y3'). This ambiguity is resolved by the use of a direction-finding antenna placed at or near the first or the second impulse radio **1504** or **1508**. The direction finding antenna can be utilized to accurately ascertain the true position of the object by determining the angular direction ϕ of the object O. An alternative method is to position two or more directional antennas such that their respective coverage areas each favor different position ambiguity areas. These antennas may be alternately selected and the relative signal strength used to determine which antenna is receiving the stronger signal. This would thus resolve the position ambiguity. The directional antennas may be electrically or mechanically steered array antennas. The details of ascertaining the true position of the object by a directional antenna are beyond the scope of the present invention and would be apparent to a person skilled in the relevant art.

[0119] In the alternative, a fourth impulse radio can be used to resolve the position ambiguity, and this is shown in **FIG. 16**. Referring now to **FIG. 16**, first, second and third impulse radios **1604**, **1608** and **1612** are placed at locations (x1, y1), (x2, y2) and (x3, y3), respectively. A fourth impulse radio **1616** is mounted on the object whose position (x4, y4) is to be determined. The object O is at a distance d_3, d_4 and d_5 from the first, second and third impulse radios **1604**, **1608**, **1612**, respectively. The distance d_1 between the first and second impulse radios and the distance d_2 between the second and the third impulse radios are known. Using methods described previously, the distances d_3, d_4 and d_5 are determined. Then, the position (x4, y4) of the object O is calculated by any known triangulation methods.

[0120] Another phenomenon known as elevation ambiguity may exist if the impulse radios of **FIG. 16** are not coplanar. The elevation ambiguity can be resolved by using a fifth impulse radio.

[0121] Recently, the mobile telephone industry has received a mandate from the Federal Communication Commission (FCC) to install position determination systems in mobile telephones. According to the FCC mandate, a mobile telephone network must be able to locate a caller of an emergency 911 call within 30 meters of accuracy. Although various technologies to implement this feature are currently being considered, no single technology has emerged as feasible.

[0122] The position determination system according to the present invention can be conveniently used to meet the FCC mandate. According to one embodiment of the present invention, an impulse radio can be used to locate the position of a mobile telephone user.

[0123] According to yet another embodiment of the present invention, a mobile telephone is equipped with an impulse radio receiver. The impulse radio receiver locks onto three beacons (or train of pulses), wherein each beacon is being transmitted by a base station. Thus, the mobile telephone simultaneously communicates with three base stations (three or more transmitted beacons are required to resolve the position ambiguity of the mobile phone). This can be performed by equipping the mobile phone with three separate cross correlators or a fast cross correlator. Other methods that are well known to a person skilled in the art can be employed to lock onto three separate beacons. Then, the time of flight of each beacon is computed by the mobile telephone. Then, using the methods described above, the position of the mobile phone is computed. Finally, the mobile telephone transmits the information to the base stations.

[0124] Several other variations of the above embodiment can be implemented. For example, a mobile telephone can be equipped with an impulse radio transmitter. The transmitter can transmit three beacons to three base stations (i.e. each base station receives a beacon). Each base station computes the distance between the mobile telephone and the base station from the time of flight of the respective beacon. The base stations then transmit the information regarding the measured distances to one of the base stations selected from the three base stations. The selected base station then computes the position of the mobile telephone using the measured distances.

[0125] In yet another embodiment of the present invention, digital data, digitized voice, and/or analog modulation may be transmitted on the data channel while positioning is independently derived from timing information. The transmitter and the receiver used in this embodiment is described in detail in U.S. Pat. No. 5,677,927 noted above.

[0126] The present invention can also be used in a GPS system to provide for greater accuracy. In fact, using the present invention, the GPS system could be updated, or another system could be deployed to deliver greater accuracy.

[0127] The principle limitation of the GPS system is that there is no convenient way to match carrier cycles with modulation cycles, making it very difficult to combine the coarse resolution available from modulation with the fine resolution available from carrier phase. Thus, designers are left with a choice between absolute range and resolution based on modulated information that is accurate within 5 meters using full military capability, and relative range based on carrier phase that is accurate within a few centimeters, but the system must start at a known point.

[0128] With a GPS system employing impulse radio transmitters and receivers, it is possible to determine the time domain equivalent of carrier phase to absolute accuracy, to thereby resolve subcycle time differences that permit range accuracy and resolution within a few centimeters. This leaves propagation effects as the largest remaining error source, since time errors and other implementation effects can generally be reduced to acceptable levels.

[0129] The claimed invention provides several solutions to problems faced by designers of position determination systems. In the past, it was not obvious to the designers how to use pulses in a practical position determination system. The problem is that it is difficult to generate a single pulse of adequate power to propagate over a useful range. The detection of a single pulse is also difficult and requires large a signal to noise ratio. The claimed invention avoids this problem by using pulse trains. With pulse trains, it is possible to add the energy from many pulses to achieve the

equivalent effect of one single pulse. In the claimed invention, time position coding of pulse trains is used so that the repeat length of a coded pulse train is longer than the distance to be measured, thus resolving a potential range ambiguity resulting from a rapid pulse rate.

[0130] In the claimed invention, the time difference between the transmitted and received pulse trains is measured indirectly by measuring the phase difference between the associated corresponding time bases that are used to generate the pulse trains. The effect of an entire pulse train is averaged in the above described loop lock filter so that pulse timing errors are reduced, while signal to noise ratio is improved by integration gain. The integration method in the cross correlator is fully described in the above noted patents. This requires extremely stable and accurate time bases. In one embodiment of the claimed invention, the time bases are generated from high frequency clocks typically phase locked to a crystal reference. The high frequency clocks are counted down using a binary counter with a modulo count equal to the modulo repeat length of the pulse position code, which is used to prevent range ambiguities from the repetitive pulse trains.

[0131] When the impulse radio position determination system is operated in an area of high multipath and/or the line of sight between the transmitter and receiver is blocked, the largest signal that the receiver may receive may not represent the shortest distance between the receiver and the transmitter. This will result in an error in the estimate of distance between the transmitter and the receiver. Specifically, the distance will be over estimated. One way to resolve this would be to allow the receiver to lock onto the largest available signal, whether a reflection or not, and then search for earlier signals with longer dwell times and narrower information bandwidths in order to find the earliest signal. In the case of urban positioning, the earliest signal may not be discernable. However, if there are a plurality of either beacons or remote receivers scattered over the area of interest, the uncertainty may be reduced by statistical methods such as finding the centroid of the area bounded by the range estimates, or the least squares of the data method or other techniques that are known to those skilled in the art.

[0132] Conclusion

[0133] While various embodiments of the present invention have been described above, it should be understood that they have been presented by way of example, and not limitation. Thus the breadth and scope of the present invention should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. In an impulse radio system having a first transceiver with a first clock providing a first reference signal and a second transceiver spaced from said first transceiver and having a second clock providing a second reference signal, a method for determining the position of the second transceiver comprising the steps of:

transmitting from said first transceiver a first sequence of pulses;

receiving said first sequence of pulses at said second transceiver;

synchronizing said second transceiver with said first sequence of pulses;

transmitting from said second transceiver a second sequence of pulses;

receiving at said first transceiver said second sequence of pulses;

synchronizing said first transceiver with said second sequence of pulses;

generating a delayed first reference signal in response to said synchronization with said second sequence of pulses; and

measuring a time difference between said delayed first reference signal and said first reference signal, said time difference indicating a total time of flight of said first and second sequence of pulses.

* * * * *

US006453168B1

(12) **United States Patent**
McCrady et al.

(10) **Patent No.:** **US 6,453,168 B1**
(45) **Date of Patent:** **Sep. 17, 2002**

(54) **METHOD AND APPARATUS FOR DETERMINING THE POSITION OF A MOBILE COMMUNICATION DEVICE USING LOW ACCURACY CLOCKS**

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(73) Assignee: **ITT Manufacturing Enterprises, Inc**, Wilmington, DE (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/365,702**

(22) Filed: **Aug. 2, 1999**

(51) **Int. Cl.^{7}** **H04B 7/00**

(52) **U.S. Cl.** **455/517**; 455/506; 455/65; 455/277.2; 455/456; 342/457; 375/347

(58) **Field of Search** 455/456, 457, 455/422, 517, 466, 67.1, 65, 59, 504, 506, 133–5, 277.1, 277.2; 342/457, 463, 357.06; 375/138, 347

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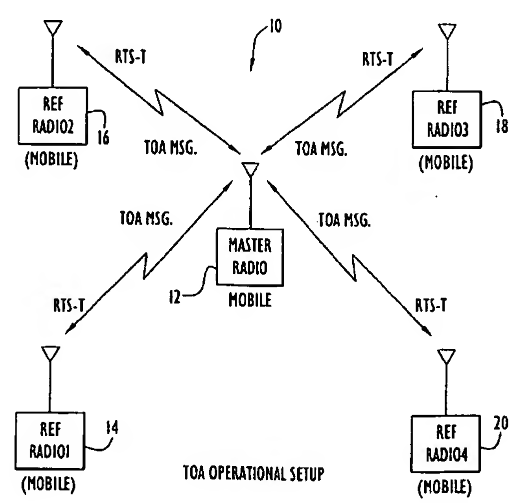
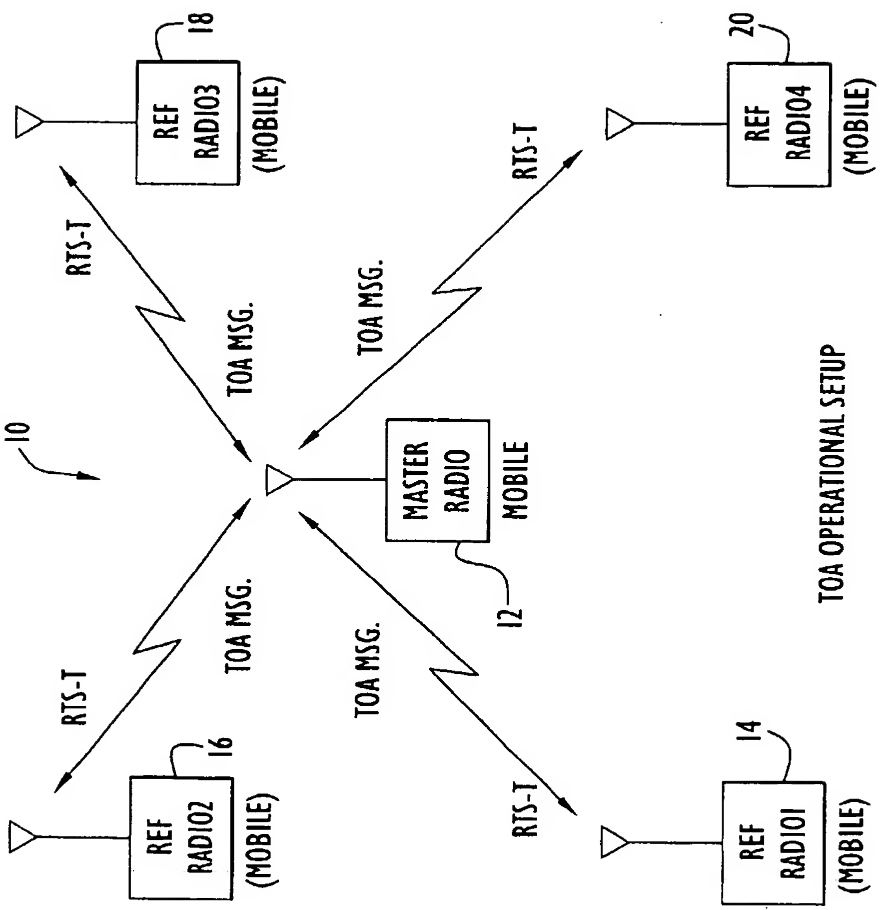
Primary Examiner—William Trost
Assistant Examiner—Philip J. Sobutka

(57) **ABSTRACT**

A spread spectrum position location communication system determines the position of a mobile master radio using a round-trip messaging scheme in which the time of arrive (TOA) of ranging messages is accurately determined to yield the range estimates required to calculate the position of the mobile radio via trilateration. The master radio transmits outbound ranging messages to plural reference radios which respond by transmitting reply ranging messages. Upon reception of the reply ranging message, the master radio determines the range to the reference radio from the signal propagation time calculated by subtracting the far-end turn around time from the round-trip elapsed time. Any combination of fixed or mobile radios of known positions can be used as the reference radios for another mobile radio in the system, thereby providing adaptability under varying transmission conditions. The individual radios do not need to be synchronized to a common time reference, thereby eliminating the need for highly accurate system clocks. By performing internal delay calibration, errors caused by difficult-to-predict internal transmitter and receiver delay variations can be minimized. Leading-edge-of-the-signal curve fitting and frequency diversity techniques minimize the effects of multipath interference on TOA estimates.

18 Claims, 6 Drawing Sheets




10
REF RADIO3
(MOBILE)
18
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20
RTS-T
TOA MSG.
RTS-T
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MASTER RADIO
MOBILE
12
TOA MSG.
RTS-T
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(MOBILE)
16
REF RADIO1
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14
TOA OPERATIONAL SETUP

FIG.1

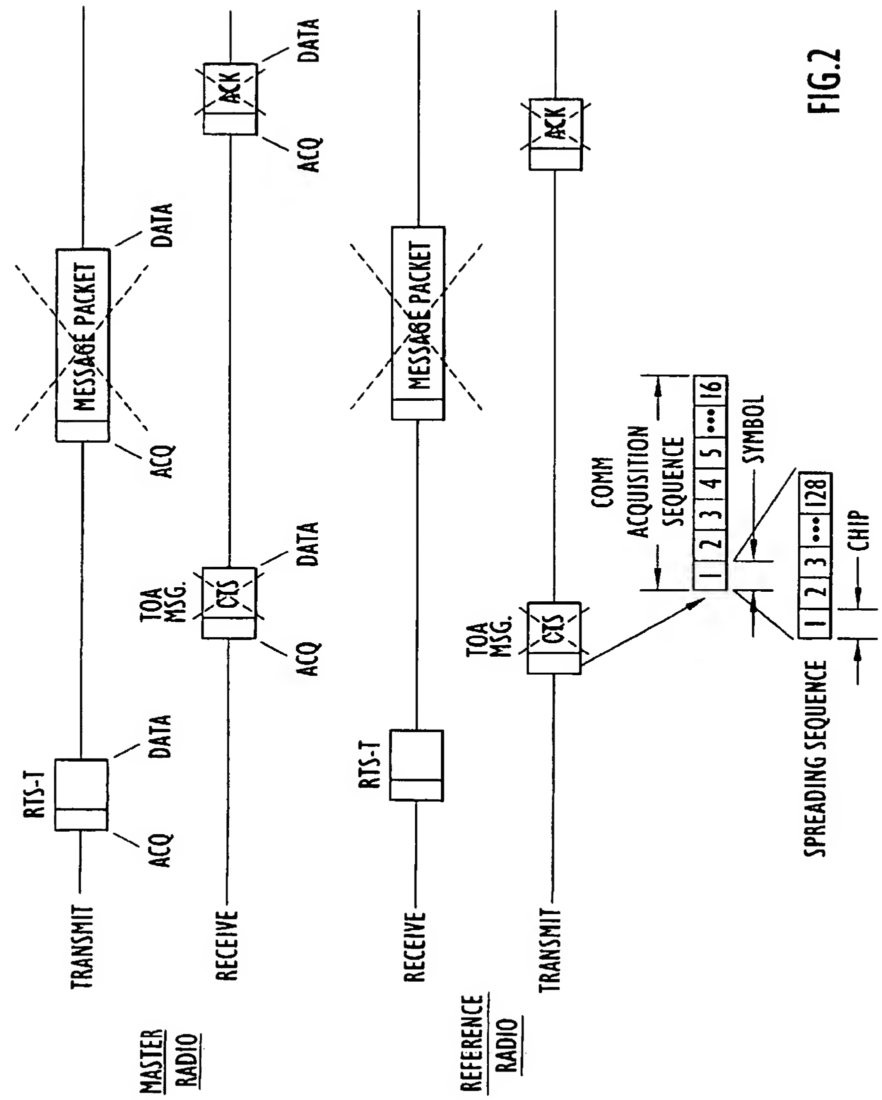

FIG.2

MODIFIED CSMA-CA PROTOCOL FOR RANGING

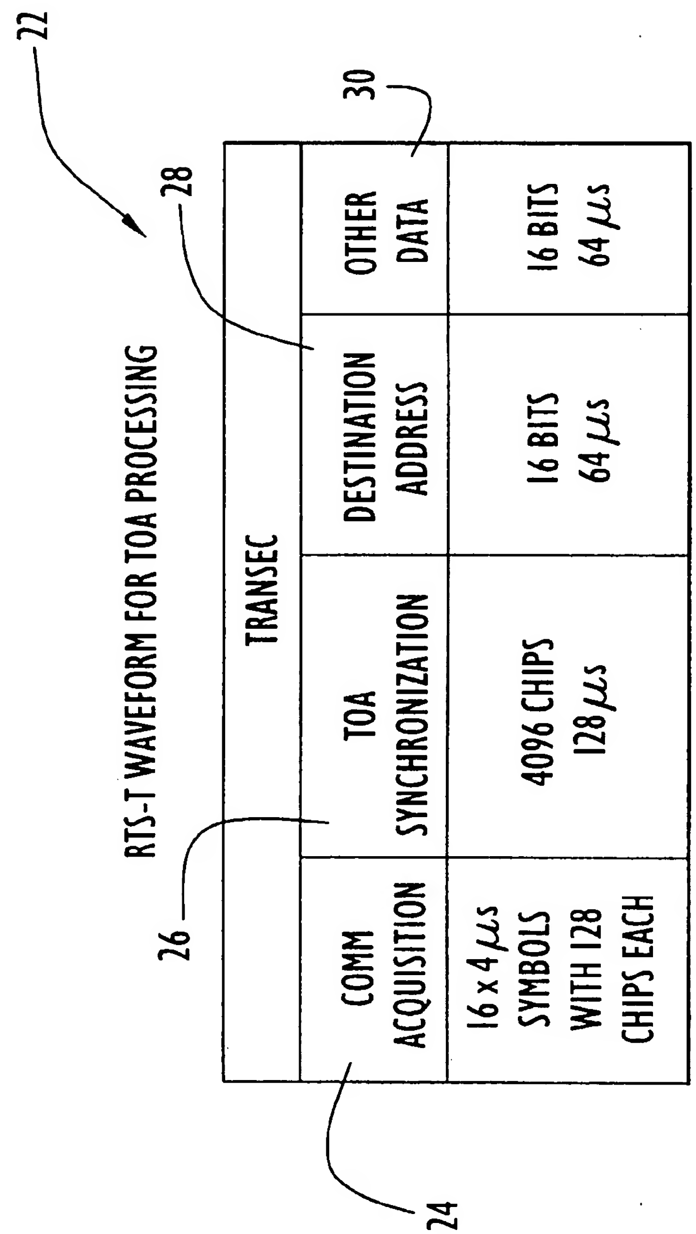
RTS-T WAVEFORM FOR TOA PROCESSING
TRANSEC
COMM ACQUISITION
16 x 4 μs SYMBOLS WITH 128 CHIPS EACH
TOA SYNCHRONIZATION
4096 CHIPS 128 μs
DESTINATION ADDRESS
16 BITS 64 μs
OTHER DATA
16 BITS 64 μs
22
24
26
28
30

FIG.3

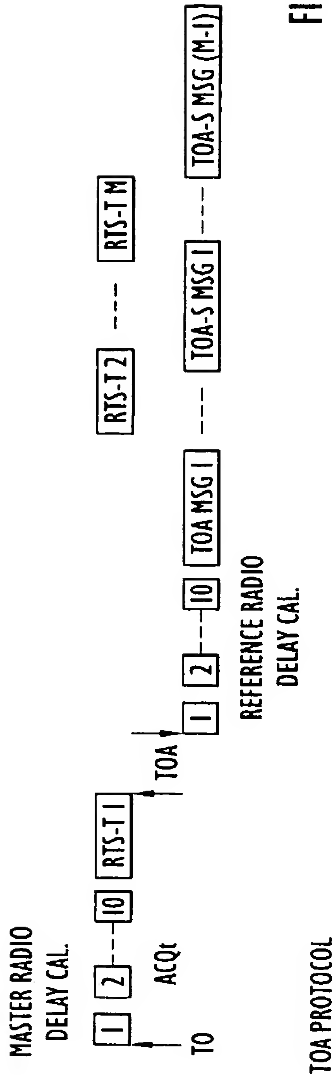
MASTER RADIO
DELAY CAL.
1
2
10
RTS-T 1
TO
ACQt
TOA
REFERENCE RADIO
DELAY CAL.
TOA MSG 1
RTS-T 2
RTS-T M
TOA-S MSG 1
TOA-S MSG (M-1)
TOA PROTOCOL

FIG.4

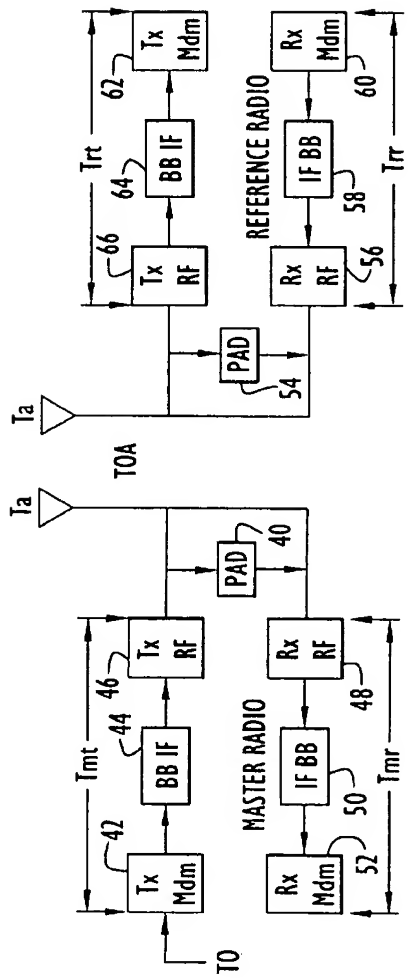
Tx Mdm
BB IF
Tx RF
Rx RF
IF BB
Rx Mdm
PAD
Ta
TO
Tmt
Tmr
MASTER RADIO
42
44
46
48
50
52
40
TOA
PAD
54
Tx RF
BB IF
Tx Mdm
Rx RF
IF BB
Rx Mdm
Trt
Trr
REFERENCE RADIO
66
64
62
56
58
60

FIG.5

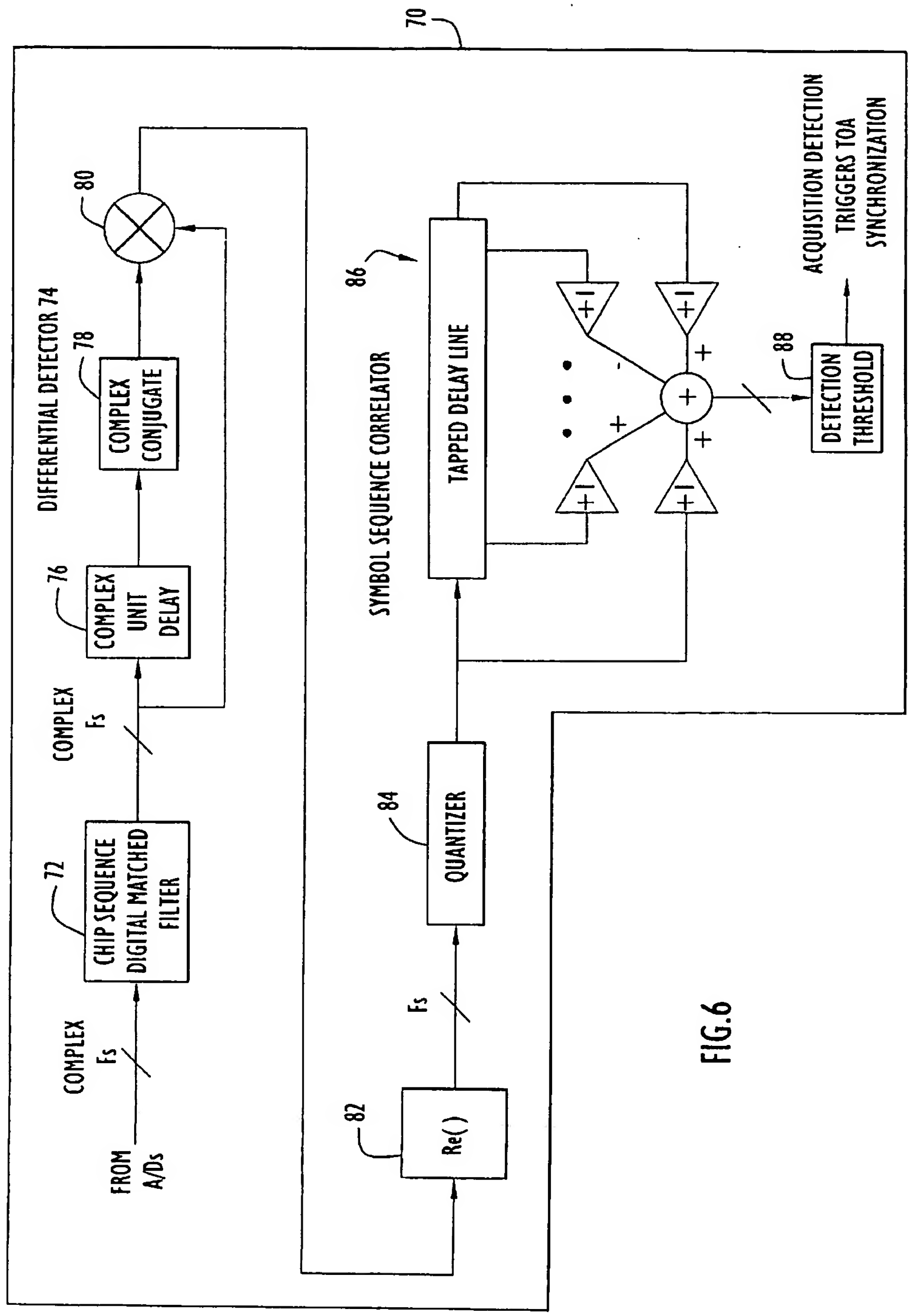
70
DIFFERENTIAL DETECTOR 74
FROM A/Ds
COMPLEX Fs
72
CHIP SEQUENCE DIGITAL MATCHED FILTER
COMPLEX Fs
76
COMPLEX UNIT DELAY
78
COMPLEX CONJUGATE
80
SYMBOL SEQUENCE CORRELATOR
82
Re( )
Fs
84
QUANTIZER
86
TAPPED DELAY LINE
88
DETECTION THRESHOLD
ACQUISITION DETECTION TRIGGERS TOA SYNCHRONIZATION

FIG.6

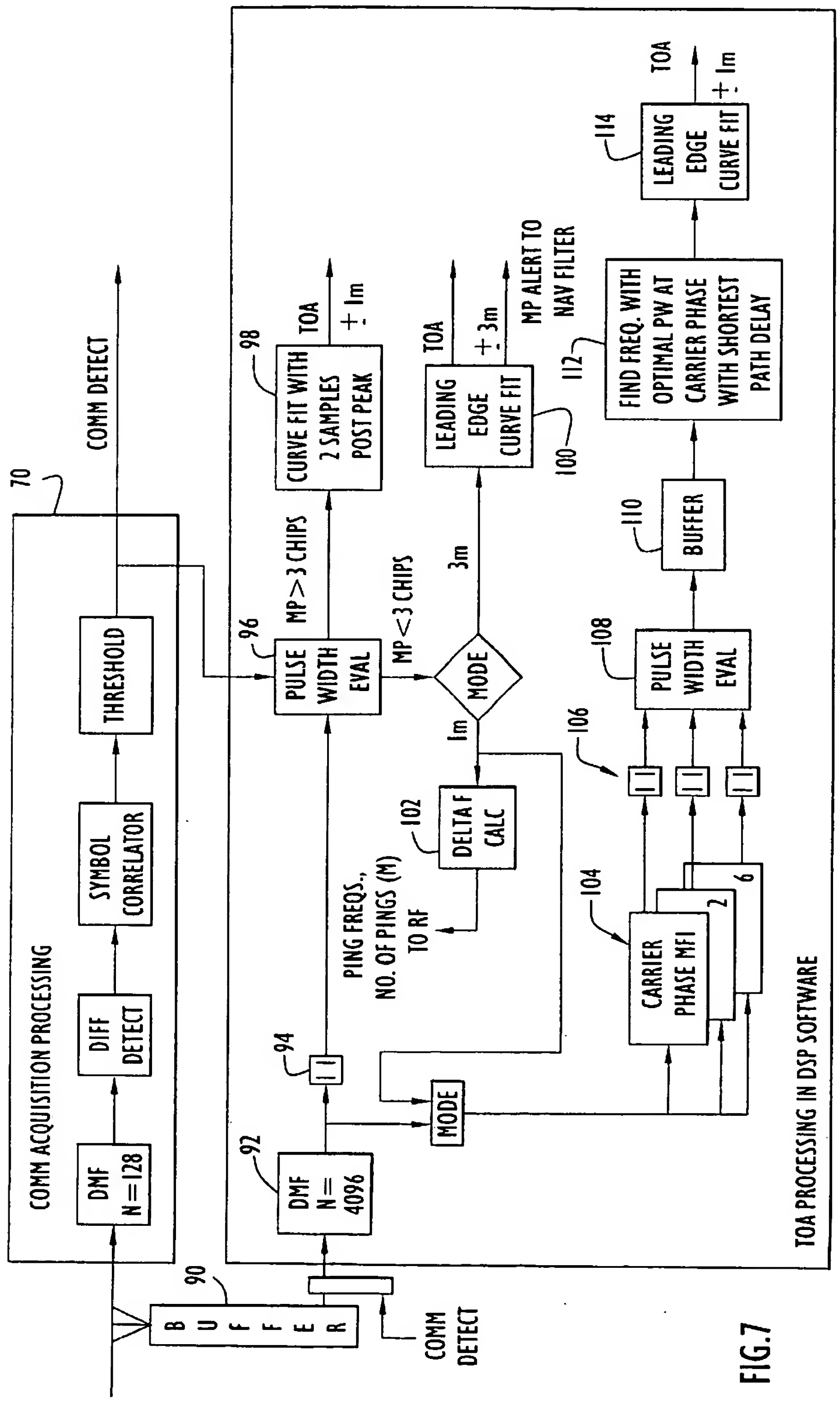
COMM ACQUISITION PROCESSING
70
DMF N=128
DIFF DETECT
SYMBOL CORRELATOR
THRESHOLD
COMM DETECT
90
BUFFER
COMM DETECT
TOA PROCESSING IN DSP SOFTWARE
92
DMF N=4096
94
MODE
PING FREQS., NO. OF PINGS (M) TO RF
96
PULSE WIDTH EVAL
MP>3 CHIPS
98
CURVE FIT WITH 2 SAMPLES POST PEAK
TOA
± 1m
MP<3 CHIPS
MODE
3m
1m
100
LEADING EDGE CURVE FIT
TOA
± 3m
MP ALERT TO NAV FILTER
102
DELTA F CALC
104
CARRIER PHASE MFI
2
6
106
108
PULSE WIDTH EVAL
110
BUFFER
112
FIND FREQ. WITH OPTIMAL PW AT CARRIER PHASE WITH SHORTEST PATH DELAY
114
LEADING EDGE CURVE FIT
TOA
± 1m

FIG.7

METHOD AND APPARATUS FOR DETERMINING THE POSITION OF A MOBILE COMMUNICATION DEVICE USING LOW ACCURACY CLOCKS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a position location system for determining the position of a mobile communication device, and, more particularly, to a system employing two-way transmission of spread spectrum ranging signals between the mobile communication device and reference communication devices having relatively low accuracy clocks, to rapidly and accurately determine the position of the mobile communication device in the presence of severe multipath interference.

2. Description of the Related Art

The capability to rapidly and accurately determine the physical location of a mobile communication device would be of great benefit in a variety of applications. In a military context, it is desirable to know the location of military personnel and/or equipment during coordination of field operations and rescue missions, including scenarios where signals of conventional position-determining systems, such as global position system (GPS) signals, may not be available (e.g., within a building). More generally, appropriately equipped mobile communication devices could be used to track the position of personnel and resources located both indoors or outdoors, including but not limited to: police engaged in tactical operations; firefighters located near or within a burning building; medical personnel and equipment in a medical facility or en route to an emergency scene, including doctors, nurses, paramedics and ambulances; and personnel involved in search and rescue operations. An integrated position location communication device would also allow high-value items to be tracked and located, including such items as personal computers, laptop computers, portable electronic devices, luggage, briefcases, valuable inventory, and stolen automobiles. In urban environments, where conventional position determining systems have more difficulty operating, it would be desirable to reliably track fleets of commercial or industrial vehicles, including trucks, buses and rental vehicles. Tracking of people carrying a mobile communication device is also desirable in a number of contexts, including, but not limited to: children in a crowded environment such as a mall, amusement park or tourist attraction; location of personnel within a building; and location of prisoners in a detention facility.

The capability to determine the position of a mobile communication device also has application in locating the position of cellular telephones. Unlike conventional land-based/wire-connected telephones, the location of conventional cellular telephones cannot automatically be determined by emergency response systems (e.g., the 911 system in the United States) when an emergency call is placed. Thus, assistance cannot be provided if the caller is unable to speak to communicate his or her location (e.g., when the caller is unconscious, choking or detained against will). The capability to determine the position of cellular telephones could be used to pinpoint the location from which an emergency call has been made. Such information could also be used to assist in cell network management.

Naturally, in cases where a mobile communication device is being used primarily to transmit or receive voice or data information, it would be desirable to incorporate position

location capabilities such that the device can communicate and establish position location at the same time without disruption of the voice or data communication.

Among convention techniques employed to determine the position of a mobile communication device is the reception at the mobile communication device of multiple timing signals respectively transmitted from multiple transmitters at different, known locations (e.g., global positioning system (GPS) satellites or ground-based transmitters). By determining the range to each transmitter from the arrival time of the timing signals, the mobile communication device can compute its position using triangulation.

The accuracy and operability of such position location techniques can be severely degraded in the presence of multipath interference caused by a signal traveling from a transmitter to the receiver along plural different paths, including a direct path and multiple, longer paths over which the signal is reflected off objects or other signal-reflective media. Unfortunately, multipath interference can be most severe in some of the very environments in which position location techniques would have their greatest usefulness, such as in urban environments and/or inside buildings, since artificial structures create opportunities for signals to be reflected, thereby causing signals to arrive at the receiver via a number of different paths.

Attempts have been made in position location systems to mitigate the effects of multipath interference. An example of a system reported to provide position location in a multipath environment is presented by Peterson et al. in "Spread Spectrum Indoor Geolocation," Navigation: Journal of The Institute of Navigation, Vol. 45, No 2, Summer 1998, incorporated herein by reference in its entirety. In the system described therein (hereinafter referred to as the Peterson system), the transmitter of a mobile radio continuously transmits a modulated pseudorandom noise (PRN) sequence, with a carrier frequency of 258.5 MHz and a chipping rate of 23.5 MHz. The transmitter is battery powered and therefore can be easily transported inside a building. Four wideband antennas located on the roof of a test site receive the signal transmitted by the mobile radio. The signals are conveyed from the antennas to four corresponding receivers via low loss cable that extends from the roof to the receivers disposed in a central location. The receivers demodulate the signal transmitted by the mobile radio using an analog-to-digital (A/D) converter board disposed inside a host personal computer (PC), which samples the signal at 1.7 s intervals for 5.5 ms and processes the raw data to determine the Time of Arrival (TOA). The system uses two receiver computers, each with a dual channel A/D board inside. The output from the receiver boxes is fed into a dual channel A/D board on two host computers. Each of the host computers processes the signal on each channel of the A/D board to determine the TOA for each channel relative to a trigger common to both channels on the A/D board. The TOA algorithm is based on finding the leading edge of the cross correlation function of the PRN sequence that is available at the output of the correlator using frequency domain techniques. TOAs are transferred via wireless local area network to the RAM-drive of a third computer acting as the base computer. From the TOAs, the base computer calculates time differences (TDs) and determines the two-dimensional position of the transmitter. This position is then plotted in real time on a building overlay.

The Peterson system suffers from a number of shortcomings. The range between the target radio and each reference radio is determined by measuring the duration of time required for a signal to travel between the radios. This

information can be determined from a one-way communication only if the target radio and the reference radios remain synchronized to the same time reference. That is, the transmitting radio establishes the time of transmission of the signal based on its local clock, and the receiving radio determines the time of arrival of the signal based on its local clock which must constantly be synchronized to the same time reference as the clock of the transmitter. The signal propagation duration can then be determined essentially by subtracting the time of transmission from the time of arrival.

Because the Peterson system uses this one-way measurement technique, the system requires synchronization between the clocks of the transmitter and the four receivers. Unfortunately, the precise time synchronization required to accurately measure the duration of the signal propagation cannot tolerate significant time drift of any local clocks over time. Consequently, all of the clocks of the system must be highly accurate (i.e., on the order of 0.03 parts per million (ppm)), thereby increasing the cost and complexity of the system.

The requirement in the Peterson system to keep the transmitter and receiver clocks synchronized has further implications on the accuracy of the position estimates made from the one-way ranging signals. Asynchronous events occur within each radio which cannot readily be characterized or predicted in advance. These events introduce errors in the radio with respect to knowledge of the actual time of transmission and time of arrival, thereby degrading the accuracy of the range and position estimates.

Developed to demonstrate the feasibility of indoor geolocation, Peterson's test system does not address a number of technical issues required to construct a commercially useful system. For example, the receiver antennas are fixedly mounted (immobile) and cabled to receivers in a remote location. Consequently, the system is not adaptable to varying transmission conditions and cannot adjust to or compensate for scenarios where the radio of interest cannot communication with one or more of the reference receivers. Signal processing and analysis are performed with standard-size personal computers and other bulky experimental equipment. The system uses a relatively low chipping rate and remains susceptible to multipath interference, impacting the accuracy and operability of the system. Further, the position of radio determined by the system is only a two-dimensional position (i.e., in a horizontal plane).

Accordingly, there remains a need for a commercially viable position location system capable of quickly and accurately determining the three-dimensional indoor or outdoor position of a compact mobile communication device in the presence of severe multipath interference for use in the aforementioned practical applications.

SUMMARY OF THE INVENTION

It is an object of the present invention to rapidly, reliably and accurately determine the three-dimensional position of a mobile communication device in a variety of environments, including urban areas and inside buildings where multipath interference can be great.

It is a further object of the present invention to provide a compact, handheld or portable mobile communication device having position location capabilities useful in a wide array of applications, including location and/or tracking of people and items such as: military personnel and equipment, emergency personnel and equipment, valuable items, vehicles, mobile telephones, children and prisoners.

It is another object of the present invention to minimize the effects of interference caused by multipath signal propagation in a position location system, thereby providing highly accurate three-dimensional position estimates even under severe multipath conditions.

It is yet another object of the present invention to reduce the cost of a position detection system by avoiding the need for synchronization to the same timing reference throughout the system, thereby eliminating the need for certain expensive components, such as highly accurate clocks.

It is a still further object of the present invention to use state-of-the-art spread spectrum chipping rates and bandwidths to reduce multipath interference and improve position measurement accuracy in a position location system.

Another object of the present invention is to separate multipath interference from direct path signals to accurately determine the time of arrival of the direct path signal to accurately determine range.

Yet another object of the present invention is to minimize errors caused by processing delays that are difficult to characterize or accurately predict.

Still another object of the present invention is to provide a self-healing system, wherein a mobile communication device can adaptively rely on any combination of fixed radios and other mobile radios to determine its own position under varying communication conditions.

A further object of the present invention is to minimize design and manufacturing costs of a position-locating mobile communication device by using much of the existing hardware and software capability of a conventional mobile communication device.

A still further object of the present invention is to incorporate position location capabilities into a mobile communication device being used to transmit or receive voice or data information, such that the device can communicate and establish its position at the same time without disruption of the voice or data communication.

The aforesaid objects are achieved individually and in combination, and it is not intended that the present invention be construed as requiring two or more of the objects to be combined unless expressly required by the claims attached hereto.

In accordance with the present invention, a position location communication system provides accurate, reliable three-dimensional position location of a handheld or portable, spread spectrum communication device within milliseconds without interruption of voice or data communications. Using spread spectrum waveforms and processing techniques, the system of the present invention is capable of determining position location to an accuracy of less than one meter in a severe multipath environment.

More particularly, the system of the present invention employs a two-way, round-trip ranging message scheme in which the time of arrive of the ranging messages is accurately determined to yield accurate range estimates used to calculate the position of a mobile radio via trilateration. A master or target mobile radio transmits outbound ranging messages to plural reference radios which respond by transmitting reply ranging messages that indicate the location of the reference radio and the message turn around time (i.e., the time between reception of the outbound ranging message and transmission of the reply ranging message). Upon reception of the reply ranging message, the master radio determines the signal propagation time, and hence range, by subtracting the turn around time and internal processing delays from the elapsed time between transmission of the outbound ranging message and the time of arrival of the

reply message. In this manner, the individual radios do not need to be synchronized to a common time reference, thereby eliminating the need for highly accurate system clocks required in conventional time-synchronized systems. The brief ranging messages can be interleaved with voice and data messages in a non-intrusive manner to provide position detection capabilities without disruption of voice and data communications.

To provide high accuracy range estimates, the time of arrival of the ranging messages are precisely estimated. By performing internal delay calibration, errors caused by difficult-to-predict internal transmitter and receiver delay variations can be minimized. The system uses state-of-the-art spread spectrum chipping rates and bandwidths to reduce multipath interference, taking advantage of existing hardware and software to carrying out a portion of the TOA estimation processing. Leading edge curve fitting is used to accurately locate the leading-edge of an acquisition sequence in the ranging message in order to further reduce effect of multipath interference on TOA estimates. The severity of multipath interference is determined by evaluating the pulse width of the acquisition sequence. If necessitated by severe multipath, frequency diversity is used to orthogonalize multipath interference with respect to the direct path signal, wherein an optimal carrier frequency is identified and used to estimate the TOA to minimize the impact of multipath interference.

Further, the system of the present invention is self-healing. Unlike conventional systems which require communication with a certain set of fixed-location reference radios, the system of the present invention can use a set of reference radios that includes fixed and/or mobile radios, wherein the set of radios relied upon to determine the location of a mobile communication device can vary over time depending on transmission conditions and the location of the mobile communication device. Any combination of fixed or mobile radios of known positions can be used as the reference radios for another mobile radio in the system, thereby providing adaptability under varying conditions.

The ranging and position location technique of the present invention is useful in wide variety of applications, including location and/or tracking of people and items such as: military personnel and equipment, emergency personnel and equipment, valuable items, vehicles, mobile telephones, children and prisoners.

The above and still further objects, features and advantages of the present invention will become apparent upon consideration of the following detailed description of a specific embodiment thereof, particularly when taken in conjunction with the accompanying drawings wherein like reference numerals in the various figures are utilized to designate like components.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic view of the operational setup of the position location system according to the present invention.

FIG. 2 is a message timing diagram illustrating a modified CSMA-CA protocol useful for exchanging ranging messages in accordance with an exemplary embodiment of the present invention.

FIG. 3 illustrates the structure of an initial outbound ranging message transmitted by the master radio in accordance with an exemplary embodiment of the present invention.

FIG. 4 illustrates the timing of the internal delay calibration performed by the master radio and reference radios during the ranging message sequence in accordance with an exemplary embodiment of the present invention.

FIG. 5 is a functional block diagram illustrating the internal delay calibration processing performed by the master radio and the reference radios in accordance with an exemplary embodiment of the present invention.

FIG. 6 is a functional block diagram illustrating the acquisition processing employed to detect the communication acquisition sequence of the ranging messages in accordance with an exemplary embodiment of the present invention.

FIG. 7 is a functional block diagram illustrating the processing performed to determine the time of arrival of a ranging message, involving evaluation and separation of multipath interference from the direct path signal.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In accordance with the present invention, a handheld or portable, spread spectrum communication device provides accurate, reliable position location information within milliseconds without interruption of voice or data communications. Using spread spectrum waveforms and processing techniques, the system of the present invention is capable of determining position location to an accuracy of less than one meter in a severe multipath environment. In particular, a two-way time-of-arrival messaging scheme is employed to achieve the aforementioned objectives, while eliminating the need for highly accurate system clocks required in conventional time-synchronized systems. By performing internal delay calibration, frequency diversity and leading-edge-of-the-signal curve fitting, a highly accurate estimate of ranging signal time of arrival can be obtained, ensuring the accuracy of the range and position calculations based thereon. Unlike conventional systems which require communication with a certain set of fixed-location reference radios, the system of the present invention can use a set of reference radios that includes fixed and/or mobile radios, wherein the set of radios relied upon to determine the location of a mobile communication device can vary over time depending on transmission conditions and the location of the mobile communication device.

Referring to FIG. **1**, a position location system **10** includes a target or "master" mobile communication device or "radio" **12** communicating with four reference communication devices **14, 16, 18** and **20**. As used herein and in the claims, a mobile communication device or mobile radio is any portable device capable of transmitting and/or receiving communication signals, including but not limited to: a handheld or body-mounted radio; any type of mobile telephone (e.g., analog cellular, digital cellular or satellite-based); a pager or beeper device; a radio carried on, built into or embedded in a ground-based or airborne vehicle; or any portable electronic device equipped with wireless transmission and reception capabilities.

Each of reference radios **14, 16, 18** and **20** can be any radio located at a known position that is capable of communicating with the master radio **12** in the manner described herein to convey position and range-related information. For example, one or more of the reference radios can be a beacon-like radio fixedly mounted in a known location, such as on a tower or building. One or more of the reference radios can also be a mobile radio capable of determining its position from others sources, such as from reception of global position system (GPS) signals or from being presently located at a surveyed position whose coordinates are

known and entered into the radio (the reference radios are not themselves GPS satellites). Finally, as explain in greater detail hereinbelow, one or more of the reference radios relied upon by a particular target radio can be another mobile communication device similar or identical to the master radio, wherein the reference radio determines its own position in accordance with the technique of the present invention (in this case, the "reference" radio functions as both a reference radio for other radios and as its own "master" radio). The fact that each reference radio could potentially be a mobile radio is indicated in FIG. 1 by the designation "(MOBILE)" next to each of reference radios **14**, **16**, **18** and **20**.

Master radio **12** communicates with the four reference radios **14**, **16**, **18** and **20** to determine its location in three dimensions. Specifically, master radio **12** and each of reference radios **14**, **16**, **18** and **20** includes an antenna coupled to a transmitter and a receiver for transmitting and receiving ranging messages. The antenna, transmitter and receiver of each radio may also be used for other communications, such as voice and data messages. The time of arrival (TOA) of ranging messages transmitted between the master and reference radios is used to determine the range to each reference radio, and trilateration is then used to determine from the range measurements the location of the master radio with respect to the reference radios. Each reference radio must know its own position and convey this information to the master radio to enable the master radio to determine its position from the ranging messages exchanged with the reference radios.

Importantly, the system of the present invention employs a two-way or round-trip ranging message scheme, rather than a one-way TOA scheme, such as those conventionally used to estimate range. As seen from the bi-directional arrows in FIG. 1, master radio **12** transmits to each of the reference radios **14**, **16**, **18** and **20** an initial outbound ranging message and receives back from each reference radio a reply ranging message. For example, master radio **12** sequentially exchanges ranging message with each individual reference radio, first exchanging ranging messages with reference radio **14**, then with reference radio **16**, etc.

By way of non-limiting example, to take advantage of existing hardware and software found in certain radios, the messaging protocol used for ranging can be derived from the Carrier Sense Multiple Access—Collision Avoidance (CSMA-CA) protocol used by these radios. As shown in FIG. **2**, the Request-to-Send (RTS) and Clear-to-Send (CTS) messages of the CSMA-CA protocol are retained to provide an initial outbound ranging message and a reply ranging message, respectively, and the Message and Acknowledgement packets of the CSMA-CA protocol need not be used. The RTS message can be adapted for use as the initial outbound ranging message transmitted from the master radio to the reference radios (designated as RTS-T in the figures), and the CTS message can be adapted for use as the reply ranging message transmitted from each of the reference radios to the master radio (designated as TOA Msg. in the figures). The format of the standard RTS and CTS messages can be modified to support the ranging messaging scheme of the present invention, as explained in greater detail hereinbelow. As with standard RTS and CTS messages, the ranging messages of the present invention can be interleaved with voice and data communication messages to permit exchange of the ranging messages without disrupting voice and data communications. Of course, it will be understood that the messaging scheme of the present invention is not limited to any particular protocol, and any suitable message structure that permits transmission of an outbound ranging message and a reply ranging message can be used to implement the present invention.

Referring again to FIG. **2**, the ranging message sequence begins with the master radio transmitting an initial outbound ranging message RTS-T to a particular reference radio (the process is repeated with each reference radio in sequence). The reference radio receives the RTS-T message after a delay proportional to the range from the master radio, and determines the time of arrival of the RTS-T message. Subsequently, the reference radio transmits a reply ranging message (TOA Msg.) to the master radio. The TOA message packet indicates the turn around time at the reference radio, i.e., the time between arrival of the RTS-T message and transmission of the corresponding TOA message. The master radio determines the time of arrival of the TOA message and derives the range to the reference radio from knowledge of the round trip delay time and the turn around time.

An example of an RTS-T waveform **22** adapted for accurately determining the time of arrival of the RTS-T message is shown in FIG. **3**. The waveform comprises an acquisition portion followed by a data portion. The acquisition portion of the waveform begins with a communication acquisition sequence (comm. acquisition) **24** comprising sixteen 4 μs symbols with **128** chips each. The communication acquisition sequence is the same as the communication acquisition sequence in a conventional RTS waveform of the CSMA-CA protocol. Consequently, existing hardware and software in the receiver of the reference radios of the exemplary embodiment can be used to detect the arrival of the RTS-T message. The acquisition portion of the RTS-T message also includes a time of arrival (TOA) synchronization sequence **26** comprising 4096 chips (128 μs in duration). As explained in greater detail hereinbelow, the TOA synchronization sequence is used in conjunction with the communication acquisition sequence to accurately determine the time of arrival.

The data portion of the RTS-T message includes a Destination Address **28** (16 bits, 64 μs) and Other Data (16 bits, 64 μs). The Destination Address field is used to indicate the reference radio to which the master radio is directing the RTS-T message. The other data field can include information such as the identification of the master radio, a flag or data indicating a ranging mode, or information relating to the state of multipath interference.

The reply ranging message (TOA Msg.) transmitted from each reference radio to the master radio also contains an acquisition portion with a communication acquisition sequence and a TOA acquisition sequence. In the data portion of the TOA message, the reference radio identifies the destination master radio and may also identify itself as the message source. The TOA message further contains an estimate of the far-end turn around time, which is the duration of time between the time of arrival of the RTS-T message at the reference radio and the time of transmission of the TOA message from the reference radio. The TOA message also contains message information indicating the present location of the reference radio. This information can be known from the fact that the reference radio is in a location whose coordinates are known, from GPS signals received and processed by the reference radio, or by employing the technique of the present invention by ranging from beacon-like radios or other mobile radios.

By precisely knowing the time of transmission of the outbound ranging message, the far-end turn around time at the reference radio (supplied to the master radio in the reply

ranging message), the time of arrival of the reply ranging message, and internal transmission/reception processing delays, the master radio can precisely determine the two-way signal propagation time between itself and each reference radio. More specifically, the two-way or round-trip propagation time (T_{RT}) is the time of arrival (TOA) of the reply message minus the time of transmission (TT) of the outbound message minus the duration of the turn around time (ΔT_{TA}) and internal processing delays within the master radio ΔT_{ID} (the internal processing delays of the reference radio are incorporated into the turn around time ΔT_{TA}).

$$T_{RT}=TOA-TT-\Delta T_{TA}-\Delta T_{ID} \quad (1)$$

Although separately represented in equation (1), the accounting for the internal processing delays can be considered part of accurately determining the time of arrival TOA and the time of transmission TT; thus, the round-trip signal propagation time T_{RT} can more generally be described as the difference between a) the elapsed time between the time of transmission of the outbound ranging message and the time of arrival of the reply ranging message and b) the turn around time ΔT_{TA}.

Once the two-way signal propagation time is determined, the range is then readily calculated as the velocity of the signal through the propagating medium (e.g., the speed of light through air) multiplied by the one-way propagation time.

$$\text{Range}=(\text{Velocity})(T_{RT})/2 \quad (2)$$

Note that the time of transmission of the outbound ranging message (TT) is known by the master radio in its own time reference frame. Likewise, the time of arrival (TOA) of the reply ranging message is known by the master radio in its own time reference frame. The turn around time (ΔT_{TA}) is an absolute time duration, unrelated to a particular timing reference of any local clock. That is, the turn around time is determined by the reference radio as the difference between the time of transmission of the reply message transmitted by the reference radio and the time of arrival of the outbound ranging message at the reference radio. While the time of arrival and time of transmission at the reference radio are determined in the time reference frame of the reference radio's local clock, the resulting time difference (ΔT_{TA}) is independent of the reference time frame of the reference radio. Thus, the round trip propagation time (T_{RT}) can be determined by the master radio in its own timing reference kept by its local clock without reference to or synchronization with the timing reference of any of the clocks of the reference radios (i.e., system synchronization is not required). In effect, the master radio "starts a timer" when the outbound ranging message is transmitted, "stops the timer" when the reply ranging message arrives, and then subtracts the turn around time and internal processing delays from the "timer's elapsed time" to obtain the duration of the round-trip signal propagation.

The two-way or round-trip messaging approach eliminates the need to synchronize the local clocks of the master radio and the reference radios to the same timing reference. Consequently, the local clocks can have a relatively low accuracy, thereby reducing system complexity and cost. That is, conventional systems that maintain synchronization of the local clocks need highly accurate clocks (e.g., 0.03 ppm) and periodic synchronization processing to prevent the clocks from drifting relative to each other over time. In contrast, the clocks of the present invention can be accurate, for example, to approximately 1 ppm. As used herein, the term "low accuracy clock(s)" refers to a clock having a low accuracy relative to the accuracy of present state-of-the-art clocks used in time-synchronized systems, specifically, an accuracy in the range between approximately 0.5 ppm and 10 ppm. While the clocks of the present invention will experience significant drift over time, this drifting does not impact system performance, because the system does not rely on synchronization of the clocks. More specifically, system of the present invention looks at the round trip delay time of signals between the master and reference radios. Even with relatively low accuracy clocks, the instantaneous or short-term drift or variation experienced by the local clock of the master radio during the brief round trip delay time, and by the local clocks of the reference radios during the even briefer turn around times, are insignificant.

As will be appreciated from the foregoing, the radios of the present invention must be able to accurately determine the time of transmission and the time of arrival of the ranging messages in order to accurately measure the range between the radios and to accurately estimate the position of the master radio. The present invention includes a number of techniques for accurately determining the true time of arrival and time of transmission, even in the presence of severe multipath interference which conventionally tends to degrade the accuracy of the time of arrival estimate.

As previously explained, asynchronous events occur within each radio which cannot readily be characterized or predicted in advance. These events introduce errors in the radio with respect to knowledge of the actual time of transmission and time of arrival, thereby degrading the accuracy of the range and position estimates. In other words, the time it takes for a signal to be processed within each radio is not constant over time, and to assume that the processing delay has a fixed value introduces inaccuracy in the time of arrival and time of transmission estimates.

According to the present invention, to minimize processing delay timing errors resulting from asynchronous events that occur within the signal processors of the radios, each radio performs an internal delay calibration in close time proximity to the transmission time of the ranging messages in order to accurately estimate the actual internal processor time delays that occur when processing the ranging messages.

Referring to FIGS. 4 and 5, the master radio initiates the TOA ranging process by performing an internal delay calibration using a loop back through pad **40** to determine internal delays (Tmt+Tmr) in the master radio for correction purposes. Multiple trials, for example ten, are performed and averaged to reduce the variance of the delay estimate. The delay Tmt is the master radio transmitter delay. It is the sum of the delays through the transmit modem (Tx mdm) **42** where the transmit signal is implemented, the transmit baseband to intermediate frequency (BB-IF) conversion **44**, and the transmit radio frequency (Tx RF) analog circuitry **46** of the master radio. The delay Tmr is the master radio receiver delay. It is the sum of the delays through the receive radio frequency (Rx RF) analog circuitry **48** of the master radio, the IF-BB conversion **50**, and the receive modem (Rx mdm) **52** where demodulation processing occurs.

Once the delay calibration is completed, the master radio begins the TOA ranging message sequence by transmitting the RTS-T outbound ranging message to the reference radio with, for example, a bit set in the TOA data field indicating the TOA ranging mode. The reference radio receives the RTS-T, reads the TOA data bit, performs an internal delay calibration using a loop back through pad **54** to determine the reference radio internal delay (Trt+Trr), curve fits to

refine the turnaround delay (as described below), and forms the TOA Message. The TOA Message includes data indicating the location of the reference radio (e.g., GPS location data), results of the delay calibration, and turnaround delay refinement from curve fitting. The delay Trr is the reference radio receiver delay. It is the sum of the delays through the Rx RF analog circuitry **56** of the radio, the IF-BB conversion **58**, and the Rx modem **60** where demodulation processing occurs. The delay Trt is the reference radio transmitter delay. It is the sum of the delays through the Tx modem **62**, the transmit BB-IF conversion **64**, and the Tx RF analog circuitry **66** of the reference radio. The TOA Message is transmitted back to the master radio which computes the final one-way TOA, range, and relative position.

The value for the master and reference radio antenna delay Ta (see FIG. **4**) is a constant preloaded into the radios and combined with the results of delay calibration to reference the TOA to the antenna/air interface. The delay Ta is determined by measuring the delay through a large sample of antennas and cabling, over a range of operating temperatures, and calculating the mean and standard deviation of the measured values. Note that cabling delays for cabling between antenna and electronics are included in Ta.

Thus, the internal processing delay of the master radio ΔT_{ID} seen in equation (1) is determined from the master radio transmitter and receiver delays Tmt and Tmr determined from the calibration process and the estimated antenna delay Ta. Similarly, the estimate of the duration of the turn around time TT includes the reference radio transmitter and receiver delays Trt and Trr determined from the calibration process and the estimated antenna delay Ta. The total elapsed time measured by the master radio between transmission of the outbound ranging message and reception the reply ranging message includes time attributable to propagation of the message signals and time attributable to processing delays within the radios. By accurately estimating and subtracting out the time attributable to processing delays, the signal propagation time (and hence the range) can be more accurately determined.

The internal delay calibration performed in the radios of the present invention is one of the keys to getting repeatable accuracy with low resolution clocks. In essence, by sending calibration signals through the same processing used to subsequently transmit the actual ranging message, the difficult-to-characterize processing delay variations can be calibrated out to yield a more accurate measurement. As shown in FIG. **4**, the master radio calibration process can be performed just prior to starting the timer measuring the duration of the round trip message time, and the reference radio calibration can be performed during the turn around time at the reference radio. More generally, the calibration in the radios can be performed at any point in time that is briefly before transmission of the ranging signals (e.g., within milliseconds). For example, if subsequent ranging messages are exchanged between the master and reference radio immediately after the initial exchange, calibration does not need to be repeated for these subsequent messages (see FIG. **4**).

Another aspect to accurately determining the range between the master radio and the reference radios is the precise estimation of the time of arrival of the outbound ranging message at the reference radio and the time of arrival of the reply ranging message at the master radio. In accordance with another aspect of the present invention, the timing of the leading edge of a synchronization sequence of the ranging message is accurately determined by assessing and avoiding multipath interference which can degrade the

accuracy of the time of arrival estimate. In particular, a two-stage signal acquisition scheme is employed using the communication acquisition sequence and the TOA synchronization sequence of the RTS-T and TOA messages. Detection of the communication acquisition sequence is used to trigger acquisition of the TOA synchronization sequence in which the time of arrival is precisely estimated.

A functional block diagram illustrating acquisition of the communication acquisition sequence of the spread spectrum RTS-T message at each reference radio (and acquisition of the TOA messages at the master radio) is shown in FIG. **6**. After analog-to-digital (A/D) conversion, the communication acquisition sequence in the form of a spread spectrum complex signal is processed to provide time synchronization for the modem of the reference radio. Specifically, the acquisition detection processing employs digital matched filtering and Barker code correlation to detect the transmitted communication acquisition waveform and to derive the required timing information. By way of example, the communication acquisition processor **70** can be configured to meet the following operational requirements: probability of detection=99.5%, probability of false alarm $=10^{-6}$, and time of detection determined to ¼ of a chip.

The communication acquisition processor **70** includes digital matched filter (DMF) **72** (N=128) having coefficients that are matched to the length 128 PN sequence that is chipping each of the sixteen, 4 μsec comm. acquisition symbols. The DMF **72** de-spreads each of the symbols and provides a peak response when aligned with each symbol. The PN sequence can be identical for each of the sixteen segments. The DMF **72** can be clocked, for example, at 32 MHz, thereby yielding 128 coefficients for the inphase (I) filter section and 128 coefficients for the quadrature (Q) filter section. The DMF coefficients can be programmable.

A differential detector **74** compares the phase of the received signal between two successive symbol intervals. More specifically, differential detector **74** includes a complex delay unit **76** which delays the output of DMF **72** by a symbol interval, a complex conjugate unit **78** which forms the complex conjugate of the delayed signal, and a comparator **80** which receives the output of DMF **72** and the delayed complex conjugate of the output of DMF **72** and produces the differential detector output. The decision variable is proportional to the phase difference between these two complex numbers, which, for BPSK, can be extracted from the real part of the differential detector output (see block **82**).

The real portion of the differential detector output is quantized in quantizer **84** and supplied to a symbol sequence correlator **86**, such as a Barker code correlator. The output of the Barker code correlator is compared to a detection threshold **88**. If the detection threshold is exceeded, a communication detection is declared.

This first stage of the two-stage signal acquisition processing (i.e., detection of the communication acquisition sequence) is the same as the processing used to detect the communication acquisition sequence of the conventional RTS message in the CSMA-CA protocol, thereby allowing existing hardware and software to be used. The communication acquisition processor **70** treats the communication acquisition sequence as a sequence of 16, 128 chip symbols and therefore employs a relatively short matched filter (N=128), resulting in a modest amount of processing. This modest processing load is desirable, since the receiver must continuously perform this processing to detect the communication acquisition sequence (whose arrival time is not known apriori).

While the detection result of the communication acquisition process can be used to estimate the TOA of the ranging message (i.e., a one-stage TOA estimation process), a more accurate estimate can be obtained by processing a longer symbol with a longer matched filter. However, continuously running a longer matched filter would require excessive processing. Accordingly, the system of present invention employs a two-stage process, wherein detection of the communication acquisition sequence triggers a second stage in which a longer acquisition symbol is processed with a longer matched filter (i.e., TOA synchronization processing). This additional processing is required only over a limited period of time identified by detection of the communication acquisition sequence, thereby preventing excessive processing.

The TOA estimation algorithm in accordance with an exemplary embodiment of the present invention is shown in FIG. 7. Note that TOA processing occurs in both the reference radio upon reception of the outbound RTS-T ranging message and in the master radio upon reception of the reply TOA ranging message. During detection processing of the communication acquisition sequence of the ranging message (block 70), the TOA synchronization sequence is buffered in buffer 90. Detection of the communication acquisition sequence triggers the TOA processor 92 to process the buffered TOA synchronization sequence. Matched filtering is performed on the 4096 chip TOA synchronization sequence using a digital matched filter (N=4096). After performing a magnitude function (block 94), the filtered TOA synchronization sequence is applied to a pulse width evaluator 96 which determines the severity of the multipath interference between the master radio and the reference radio at the frequency of the ranging message. Essentially, a replica of the TOA synchronization sequence's multipath-free correlation function out of the matched filter is stored in the pulse width evaluator 96 (i.e., the multipath-free pulse shape profile is known). Pulse width evaluator 96 moves the pulse shape replica through the profile of the output of the matched filter 92 and performs a least-mean-square error fit to achieve a rough curve fitting between the replica pulse shape and the matched filter output to identify the timing of the direct path signal and subsequent multipath signals (at the time of the direct path signal and the multipath signal, the matched filter profile will be similar to the replica profile). In this manner, the pulse width evaluator 96 can determine the separation, in terms of chips, between the direct path signal and the closest substantial multipath interference signal.

The TOA processor can be configured to provide one or more levels of TOA accuracy. In the embodiment shown in FIG. 7, the TOA processor is capable of providing two selectable levels of accuracy; a one meter accuracy and a three meter accuracy (the accuracy refers to the resultant range estimate). The desired accuracy mode can be set by the master radio or by a system controller and can be conveyed to the reference radio in the initial RTS-T message or another preceding message.

If the pulse width evaluator determines that the multipath interference is separated from the direct path signal by more than a predetermined number of chip widths, the multipath interference is classified as insubstantial in terms of impacting the TOA estimate. In the exemplary embodiment shown in FIG. 7, if the multipath interference is separated from the direct path signal by more than three chip widths, the multipath interference is considered to be insubstantial. Optionally, more than one chip width threshold can be used to provide a more refined estimate of the severity of multipath interference.

When the multipath interference is judged by the pulse width evaluator 96 to be insubstantial, the TOA estimate is obtained via a curve fitting algorithm using the leading edge samples plus two samples after the peak. Post peak samples can be used because the multipath will not corrupt them in this case. A high accuracy TOA measurement (e.g., one meter accuracy) is attained in this case, regardless of the selected accuracy mode.

The resulting TOA measurement is processed in the aforementioned manner to accurately determine the range between the master radio and the reference radio (i.e., at the reference radio the TOA estimate is used to accurately determine the turn around time, and at the master radio, the TOA estimate is used to accurately determine the round trip propagation time). The resulting range estimate, together with the TOA accuracy estimate (e.g., one meter or three meters) is supplied to a navigation Kalman filter (not shown) which tracks the location solution of the master radio.

In accordance with the exemplary embodiment shown in FIG. 7, if the pulse width evaluator 96 determines that the separation between the direct path signal and the nearest multipath signal is less than a predetermined number of chip widths (e.g., three), the multipath interference is classified as substantial. In this case, the processing differs, depending on whether a high accuracy (e.g., one meter) TOA mode or a lower accuracy (e.g., three meter) TOA mode has been selected. If a lower accuracy (e.g., three meters) mode has been selected, a leading edge curve fit 100 is implemented to estimate the TOA. Note that, in this case, post peak samples are not used, since multipath interference would likely corrupt these samples. In addition to reporting the lower accuracy of the TOA estimate to the Kalman filter, a multipath alert is passed on to the Kalman filter to reduce the associated filter gain.

On the other hand, if the multipath interference is classified as substantial and the high accuracy (e.g., one meter) mode has been selected, the TOA processor implements a process employing frequency diversity to identify an optimal transmission frequency that minimizes multipath interference. Note that the capability to declare that frequency diversity processing is to be carried out can reside in one or both of the reference radio (upon processing the outbound RTS-T ranging message) and the master radio (upon processing the reply TOA ranging message).

Taking the case where the master radio is configured to declare the need for frequency diversity, the master radio identifies the set of M carrier frequencies that will be used to transmit a sequence of M outbound ranging messages and M corresponding reply ranging messages (block 102). If the reference radio is configured to declare the need for frequency diversity processing, it can notify the master radio in the reply TOA ranging message of the need to initiate this process. These frequencies are referred to as "ping" frequencies, since a rapid succession of M different frequency signals or multiple "pings" are transmitted between the radios in search of an optimal frequency. Using the pulse width information, the number of pings and the ping frequencies are determined and the control information is transferred to the RF subsystem of the master radio. Diverse frequencies create diverse carrier phases in multipath. Ranging performance is best when the carrier phase of the multipath is 90° with respect to the direct path. If this orthogonality condition is met, the direct path and multipath are separated such that the direct path can be more precisely curve fit with minimal effects for multipath.

The selection of the number M of ping frequencies and the individual ping carrier frequencies can be determined in any

of number of ways. For example, a fixed number of carrier frequencies (e.g., M=8, including the first frequency already transmitted) at set frequencies covering a predetermined frequency range can be used (e.g., carrier frequencies at 2 MHz increments covering a 15 MHz range). Alternatively, the number of trials/frequencies can be selected from 1 to M depending on the severity of the multipath. More generally, ping frequencies can be calculated or predetermined to effectively rotate the inphase and quadrature samples at the output of the DMF through the carrier phase in 15° increments (or other increments) to find the frequency that best orthogonalizes the phase of the multipath interference with respect to the direct path signal.

Once the number M of ranging message exchanges and ping frequencies are determined or selected, the next M-1 TRS-T/TOA message exchanges are transmitted, using different carrier frequencies for each exchange. These subsequent M-1 RTS/TOA message exchanges can use shortened packets that include the acquisition portion and radio identification numbers (designated with an "S" suffix on the TOA messages in FIG. 4). Delay calibrations and GPS data are not required due to the rapid rate at which these packets are exchanged.

Referring again to FIG. 7, the TOA processor processes the communication acquisition sequence and the TOA synchronization sequence of each of the M ranging messages in the same manner as the initial ranging message. Specifically, upon detection of the communication acquisition sequence, the TOA synchronization sequence is match filtered (taking into consideration the carrier frequency), the magnitude is determined, and the resulting signal is evaluated by a pulse width evaluator to determine the proximity of the multipath interference to the direct path signal (see blocks **104**, **106** and **108**). The results of the pulse width evaluation from each of the M ranging messages and the output of the matched filter are stored in a buffer **110**. Upon completion of the M trials, the frequency having the best multipath discrimination is identified (block **112**) and a leading edge curve fit **114** is performed on the output of the corresponding matched filter to estimate the TOA. Specifically, the data is searched to find the frequency where the optimal pulsewidth occurs at the carrier phase with the shortest path delay. The resulting TOA measurement is processed in the aforementioned manner to accurately determine the range between the master radio and the reference radio, and the range estimate and TOA accuracy estimate are supplied to the navigation Kalman filter to update the master radio's position.

Note that the TOA synchronization sequence is not strictly required by the system of the present invention; the receiver can directly use the communication acquisition sequence to evaluate multipath interference and curve fit to determine the leading edge of the signal. For example, the communication acquisition sequence can be continuously buffered and, upon detection, a longer matched filter (N=2048) treating the communication acquisition sequence as one long symbol can be used to perform the TOA estimation. In this case, the relatively rough estimate of the TOA provided by the communication acquisition processing can be used to limit the time range over which the TOA processor match filters the communication acquisition sequence with the 2048 length matched filter. The TOA processing is otherwise similar to the TOA processing shown in FIG. 7 (the DMF would be 2048 chips long rather than 4096). However, a more precise estimate can be obtained using the TOA synchronization sequence described above, since the 4096 chip TOA synchronization sequence yields superior signal properties, such as lower sidelobes.

While a particular implementation of the TOA processing has been described in conjunction with FIG. 7, it will be understood that other implementation and variations in the TOA processing scheme fall within the scope of the invention. For example, if a high accuracy TOA mode is selected, the radios can automatically exchange ranging messages at M different frequencies without first evaluating at a first frequency whether multipath interference is substantial (as is required in the above-described algorithm), and a single ranging message exchange can always be used in the lower accuracy TOA mode. While automatically requiring transmission of multiple round-trip ranging messages in the high accuracy mode, this approach could potentially provide a simpler messaging implementation, since there are no contingencies for determining whether or not to transmit additional ranging messages after the first message exchange.

The master radio determines its own position from the measured range to each of the reference radios via a trilateration technique which can be for example, a conventional trilateration technique. Once the master radio's position has been determined, the master radio can convey this information to other radios or to a controller or coordinator performing tracking and/or mapping of the master radio and perhaps other associated mobile radios. The ranging/position location processing can be performed periodically or initiated by the master radio or a system controller as needed.

As will be understood from the above description, the mobile communication device allows the position location system of the present invention to be self-healing. That is, in situations with a number of mobile radios, each mobile radio may be able to serve as both a master radio to determine its own position and as a reference radio for other mobile radios. Thus, when a particular mobile radio cannot receive adequate ranging signals from a current set of reference radios, the mobile radio can alter the set of reference radios to include mobile radios whose ranging signals are acceptable. For example, a first mobile radio may be relying on four reference radios that are fixed or GPS-based. A second mobile radio may be positioned such that the signal strength from one of the fixed or GPS-based reference radios is too weak or the positional geometry is such that the four fixed/GPS-based reference radios do not provide accurate three-dimensional information (e.g., two are along the same line of sight). In this case, the second mobile radio can use the first mobile radio as one of the reference radios if this provides better results. This flexibility is in contrast to conventional systems where the mobile radios must rely on fixed transmitters for reception of ranging signals and cannot range off of other mobile radios to determine position.

While shown in FIG. 1 as communicating with four reference radios, it will be understood that the master radio of the present invention can communicate ranging messages with any plurality of reference radios. For example, the master radio can determine some position information from communication with as few as two reference radios. Further, the master radio can exchange ranging messages with more than four reference radios and dynamically select the best four range measurement each time the position location process is performed, based on signal strength of the TOA messages, geometry, etc. In this way, for example, the master radio can determine and use its four nearest neighbors as the reference radios.

The hardware required to implement the system of the present invention easily fits within the physical footprint of a handheld spread spectrum radio, permitting the system to be used in a wide variety of applications. For example, to

provide situation awareness in military exercises, the system of the present invention can be used to determine and track the location of military personnel and/or equipment during coordination of field operations. This would be particularly useful in scenarios where GPS signals are weak or unavailable due to atmospheric conditions, terrain or location of the radio inside a building, or to augment and enhance the accuracy of GPS position information. The position information can be used by a commander to dynamically map the current position of personnel and equipment and to coordinate further movements. Further, individual mobile radios can receive and display position information for other related personnel, so that soldiers in the field are provided with situation awareness for their immediate surroundings.

The system of the present invention can also be used to locate and track non-military personnel and resources located both indoors or outdoors, including but not limited to: police engaged in tactical operations; firefighters located near or within a burning building; medical personnel and equipment in a medical facility or en route to an emergency scene; and personnel involved in search and rescue operations.

The system of the present invention can also be used to track high-value items by tagging items or embedding a mobile radio in items such as personal computers, laptop computers, portable electronic devices, luggage (e.g., for location within an airport), briefcases, valuable inventory, and stolen automobiles.

In urban environments, where conventional position determining systems have more difficulty operating, the system of the present invention could reliably track fleets of commercial or industrial vehicles, including trucks, buses and rental vehicles equipped with mobile radios. Tracking of people carrying a mobile communication device is also desirable in a number of contexts, including, but not limited to: children in a crowded environment such as a mall, amusement park or tourist attraction; location of personnel within a building; and location of prisoners in a detention facility. The mobile radio could be carried on the body by incorporating the radio into clothing, such as a bracelet, a necklace, a pocket or the sole of a shoe.

The system of the present invention also has application in locating the position of cellular telephones. By building into a conventional mobile telephone the ranging and position location capabilities of the present invention, the location of the telephone can be determined when an emergency call is made or at any other useful time. This capability could also be used to assist in cell network management (i.e., in cell handoff decisions).

While the present invention has been described above in the context of a system that transmits and receives electromagnetic signals through the air, it will be appreciated that the two-way round-trip ranging technique, including the internal delay calibration and TOA processing can be used in other mediums and with other types of signals, including, but not limited to: electromagnetic signals transmitted through solid materials, water or in a vacuum; pressure waves or acoustic signals transmitted through any medium (e.g., seismic, sonar or ultrasonic waves).

Having described preferred embodiments of new and improved method and apparatus for determining the position of a mobile communication device using low accuracy clocks, it is believed that other modifications, variations and changes will be suggested to those skilled in the art in view of the teachings set forth herein. It is therefore to be understood that all such variations, modifications and changes are believed to fall within the scope of the present invention as defined by the appended claims.

What is claimed is:

1. A mobile communication device capable of determining range to a reference communication device by exchanging ranging signals with the reference communication device, comprising:

a transmitter configured to transmit to the reference communication device a sequence of outbound ranging signals at different carrier frequencies;

a receiver configured to receive from the reference communication device a sequence of reply ranging signals at the different carrier frequencies in response to the outbound ranging signals; and

a processor configured to select from among the reply ranging signals a reply ranging signal at a carrier frequency providing a highest signal timing accuracy, said processor determining a time of arrival of the selected reply ranging signal and the range to the reference communication device from a round-trip signal propagation time of the selected reply ranging signal and a corresponding outbound ranging signal.

2. The mobile communication device of claim 1, wherein said processor selects the reply ranging signal whose carrier frequency minimizes multipath interference.

3. The mobile communication device of claim 1, wherein said processor estimates the time of arrival of the selected reply ranging signal using signal curve fitting and computes the range to the reference communication device using a timing adjustment determined from the signal curve fitting.

4. The mobile communication device of claim 3, wherein:

the reference communication device estimates the time of arrival of the outbound ranging signals using signal curve fitting; and

said processor of the mobile communication device computes the range to the reference communication device using a timing adjustment determined from the signal curve fitting performed by the reference communication device on the outbound ranging signal corresponding to the selected reply ranging signal.

5. The mobile communication device of claim 1, wherein said mobile communication device performs internal delay calibration to reduce errors in estimating a time of arrival of the reply ranging signal and computes the range to the reference communication device using a timing delay determined from the internal delay calibration.

6. The mobile communication device of claim 5, wherein:

the reference communication device performs internal delay calibration to reduce errors in estimating a time of arrival of the outbound ranging signals; and

said processor of the mobile communication device computes the range to the reference communication device using a timing delay determined from the internal delay calibration performed by the reference communication device.

7. The mobile communication device of claim 1, wherein said mobile communication device determines ranges to a plurality of reference communication devices by exchanging ranging signals with each of the reference communication devices, said processor determining the position of said mobile communication device from known positions of said reference communication devices and the range to each of said reference communication devices.

8. The mobile communication device of claim 1, further comprising:

a low accuracy clock adapted to maintain a local timing reference, said mobile communication device determining a time of transmission of the outbound ranging

signals and a time of arrival of the reply ranging signals in accordance with the local timing reference, said low accuracy clock not being synchronized with a clock maintaining a local timing reference for the reference communication device.

9. The mobile communication device of claim 1, wherein said mobile communication device is a handheld device.

10. A mobile communication device capable of determining range to a reference communication device by exchanging ranging signals with the reference communication device, comprising:

means for transmitting to the reference communication device a sequence of outbound ranging signals at different carrier frequencies;

means for receiving from the reference communication device a sequence of reply ranging signals at the different carrier frequencies in response to the outbound ranging signals;

means for selecting from among the reply ranging signals a reply ranging signal at a carrier frequency providing a highest signal timing accuracy; and

means for determining a time of arrival of the selected reply ranging signal and the range to the reference communication device from a round-trip signal propagation time of the selected reply ranging signal and a corresponding outbound ranging signal.

11. The mobile communication device of claim 10, wherein said selecting means selects the reply ranging signal whose carrier frequency minimizes multipath interference.

12. The mobile communication device of claim 10, wherein said mobile communication device determines ranges to a plurality of reference communication devices by exchanging ranging signals with each of the reference communication devices, said mobile communication device further comprising:

means for determining the position of said mobile communication device from known positions of said reference communication devices and the range to each of said reference communication devices.

13. A method of determining the range between a mobile communication device and a reference communication device, comprising the steps of:

(a) transmitting a sequence of outbound ranging signals at different carrier frequencies from the mobile communication device to the reference communication device;

(b) transmitting a sequence of reply ranging signals at the different carrier frequencies from the reference communication device to the mobile communication device in response to the outbound ranging signals; and

(c) determining the range between the mobile communication device and the reference communication device from a round-trip signal propagation time of a selected outbound ranging signal and a corresponding reply ranging signal transmitted at a carrier frequency providing a highest signal timing accuracy.

14. The method of claim 13, wherein steps (a), (b) and (c) are repeated with the mobile communication device and a plurality of reference communication devices, the method further comprising the step of:

(d) determining the position of the mobile communication device from known positions of the reference communication devices and the range to each reference communication device.

15. The method of claim 13, wherein the selected outbound ranging message and the corresponding reply ranging message are selected to minimizes multipath interference.

16. A position location system for determining the position of a mobile communication device, comprising:

a plurality of reference communication devices having known positions, each configured to transmit and receive ranging signals; and

a mobile communication device configured to exchange ranging signals with said reference communication devices, said mobile communication device transmitting to each reference communication device a sequence of outbound ranging signals at different carrier frequencies, each of said reference communication devices transmitting a sequence of reply ranging signals at the different carrier frequencies in response to the outbound ranging signals, wherein;

said mobile communication device determines the range to each reference communication device from a round-trip signal propagation time of a selected outbound ranging signal and a corresponding reply ranging signal transmitted at a carrier frequency providing a highest signal timing accuracy, and determines the position of said mobile communication device from the known positions of said reference communication devices and the range to each reference communication device.

17. The system of claim 16, wherein, for each reference radio, said mobile communication device selects the reply ranging signal whose carrier frequency minimizes multipath interference.

18. The system of claim 16, wherein at least one of said reference communication devices is another mobile communication device.

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